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(54) **METHOD OF FORMING A STRUCTURE ON A SUBSTRATE**

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(58) **Field of Classification Search**
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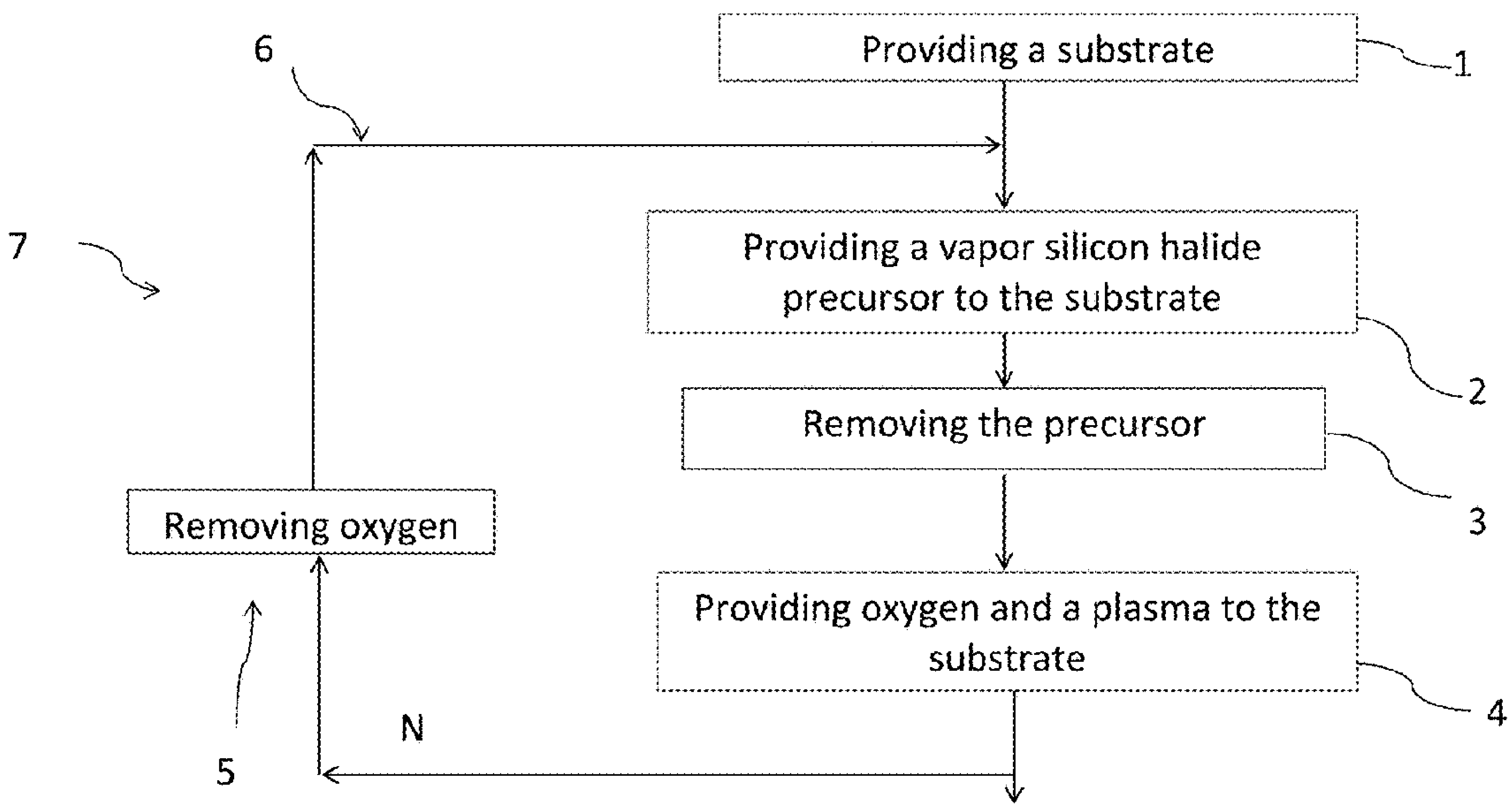
(57) **ABSTRACT**

The invention relates to a method of providing a structure by depositing a layer on a substrate in a reactor. The method comprising:

introducing a silicon halide precursor in the reactor;
introducing a reactant gas comprising oxygen in the reactor; and,
providing an energy source to create a plasma from the reactant gas so that the oxygen reacts with the first precursor in a layer comprising silicon dioxide.

16 Claims, 5 Drawing Sheets



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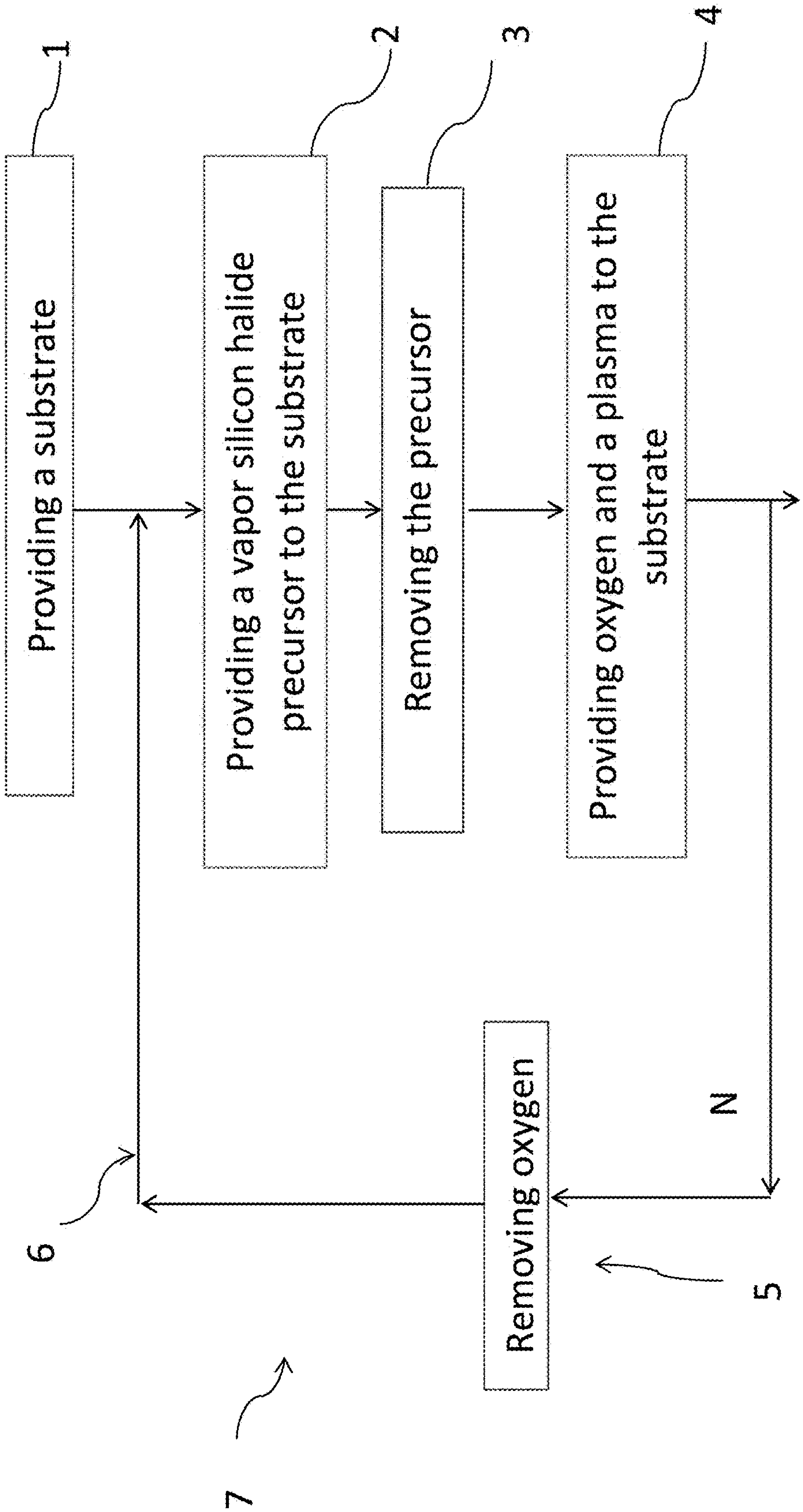

Providing a substrate
Providing a vapor silicon halide precursor to the substrate
Removing the precursor
Providing oxygen and a plasma to the substrate
Removing oxygen
N
1
2
3
4
5
6
7

FIG. 1

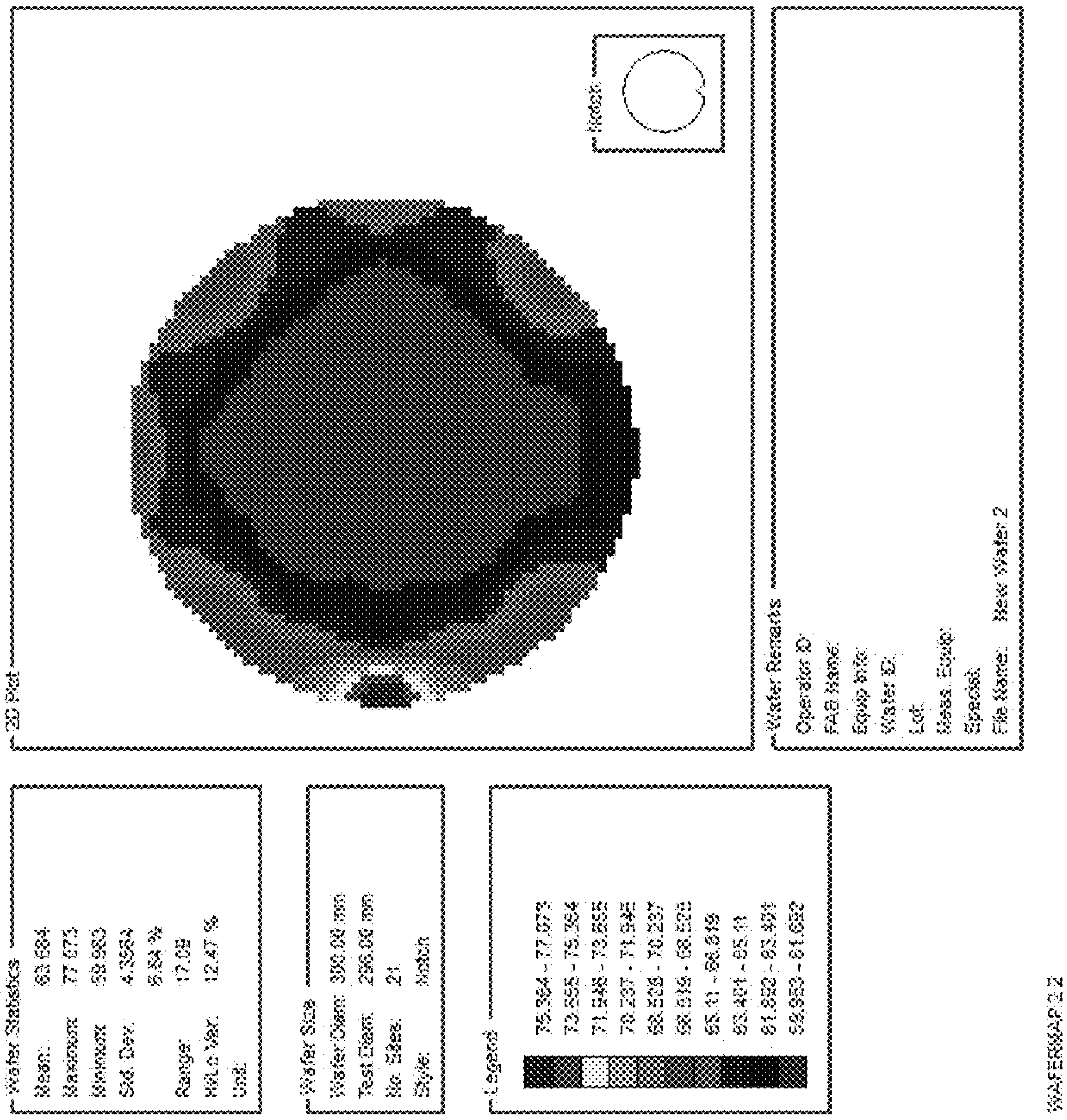


FIG. 2b

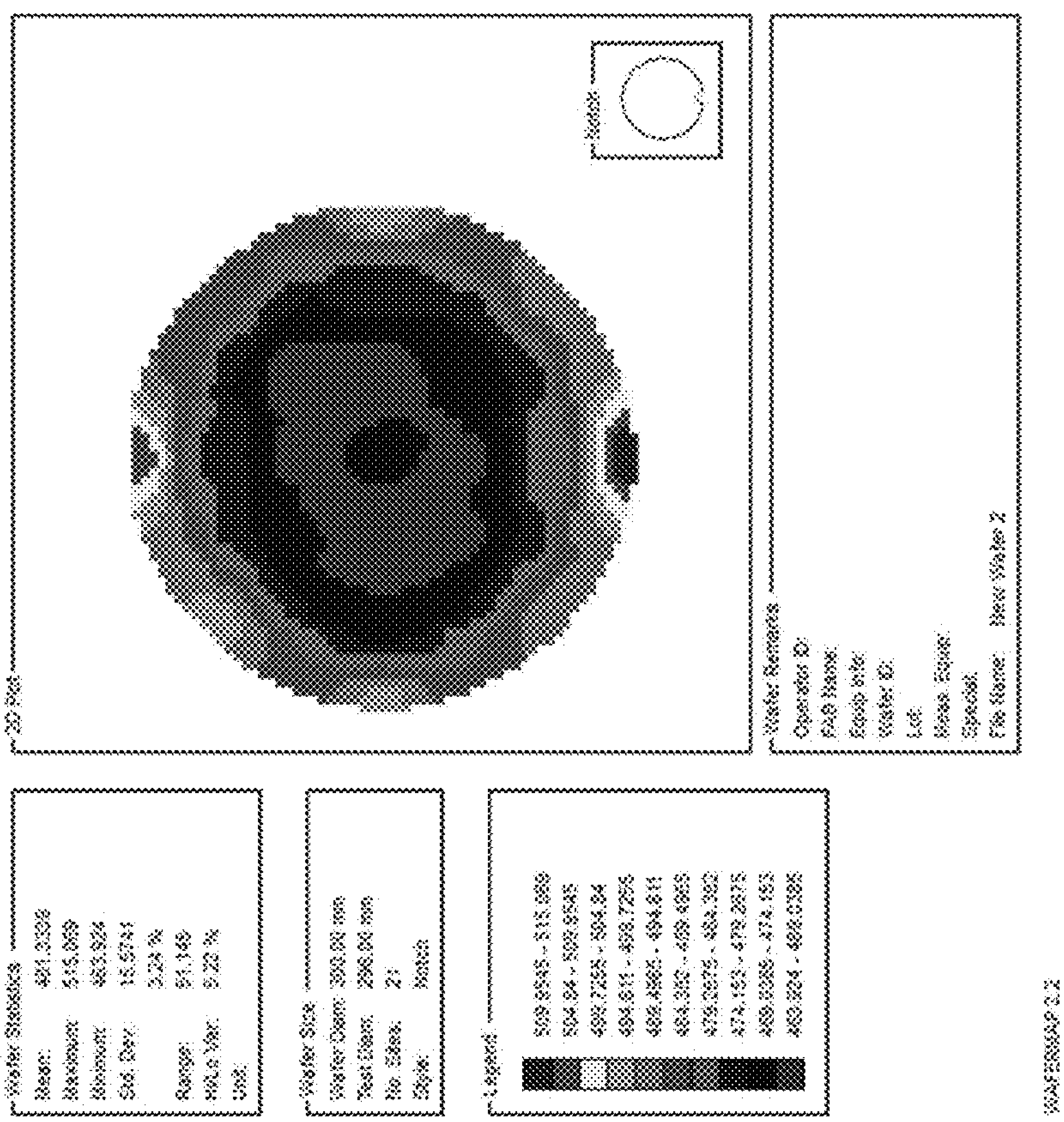
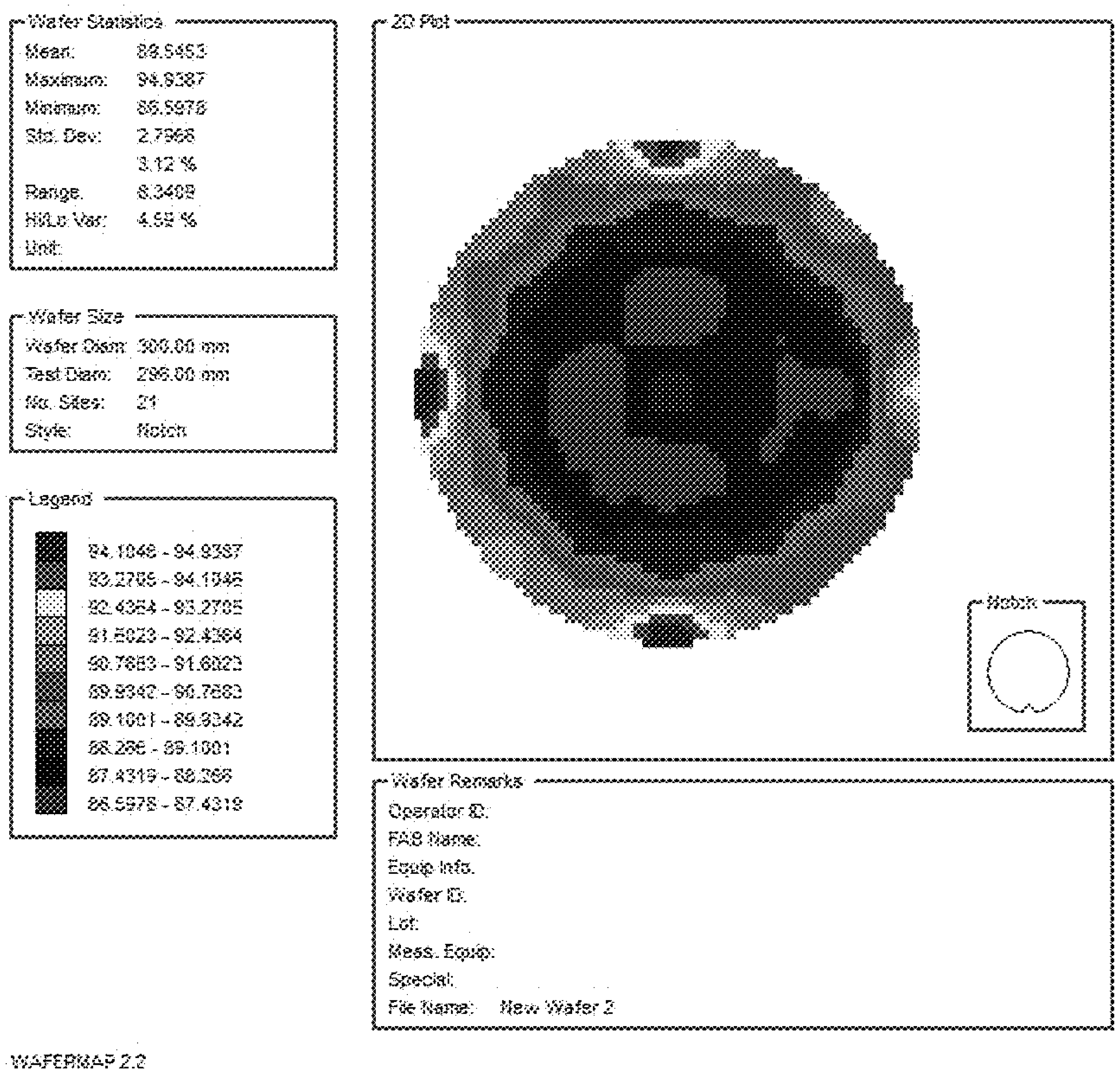


FIG. 2a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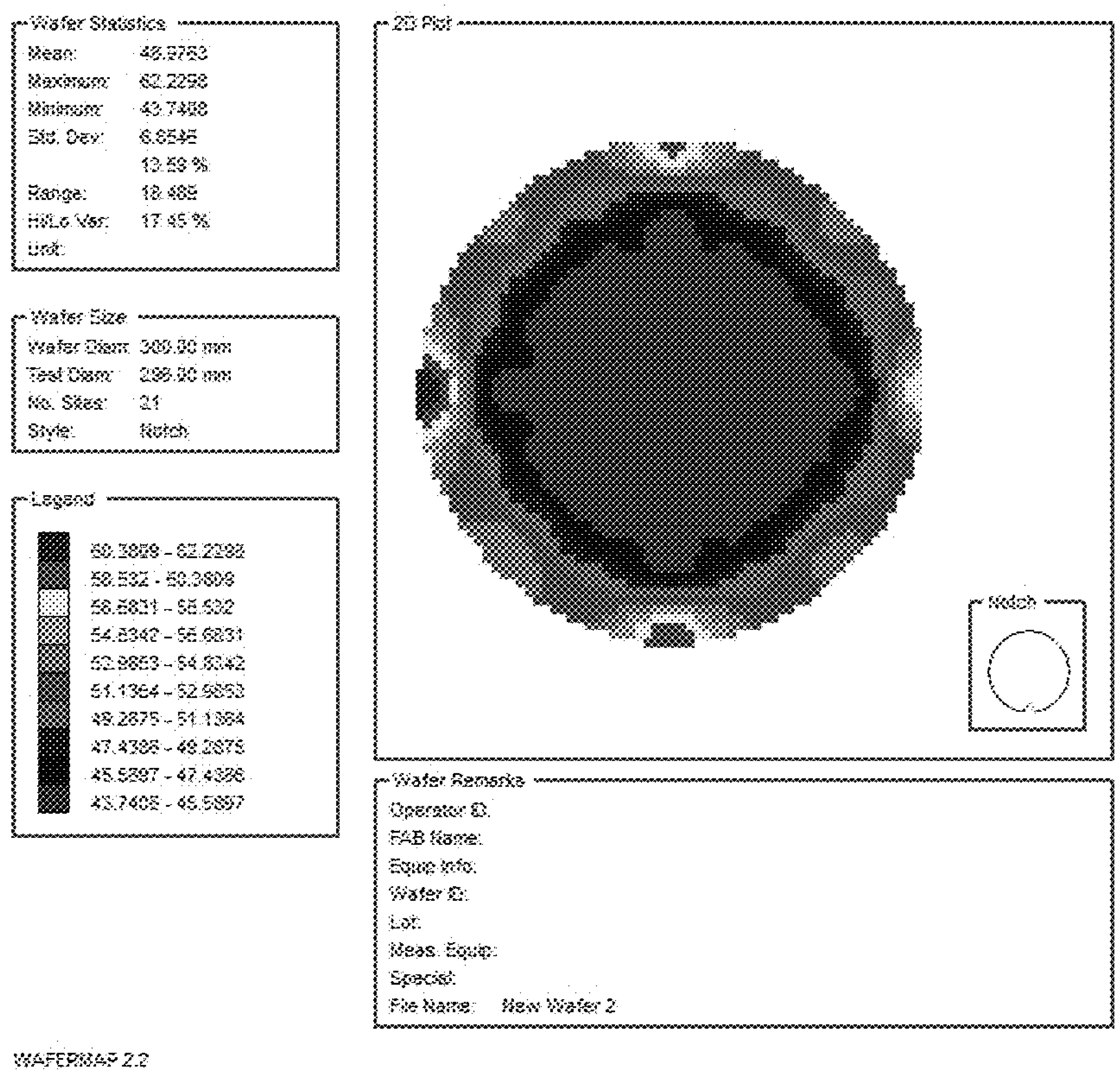
Range: 8.3409
Hi/Lo Var: 4.59 %
Unit:
Wafer Size
Wafer Diam: 300.00 mm
Test Diam: 296.00 mm
No. Sites: 21
Style: Notch
Legend
94.1048 - 94.9387
93.2706 - 94.1048
92.4364 - 93.2706
91.6023 - 92.4364
90.7683 - 91.6023
89.9342 - 90.7683
89.1001 - 89.9342
88.266 - 89.1001
87.4319 - 88.266
86.5978 - 87.4319
2D Plot
Notch
Wafer Remarks
Operator ID:
FAB Name:
Equip Info:
Wafer ID:
Lot:
Meas. Equip:
Special:
File Name: New Wafer 2
WAFERMAP 2.2

FIG. 3a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Minimum: 43.7408
Std. Dev: 6.6545
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Range: 18.489
Hi/Lo Var: 17.45 %
Unit:
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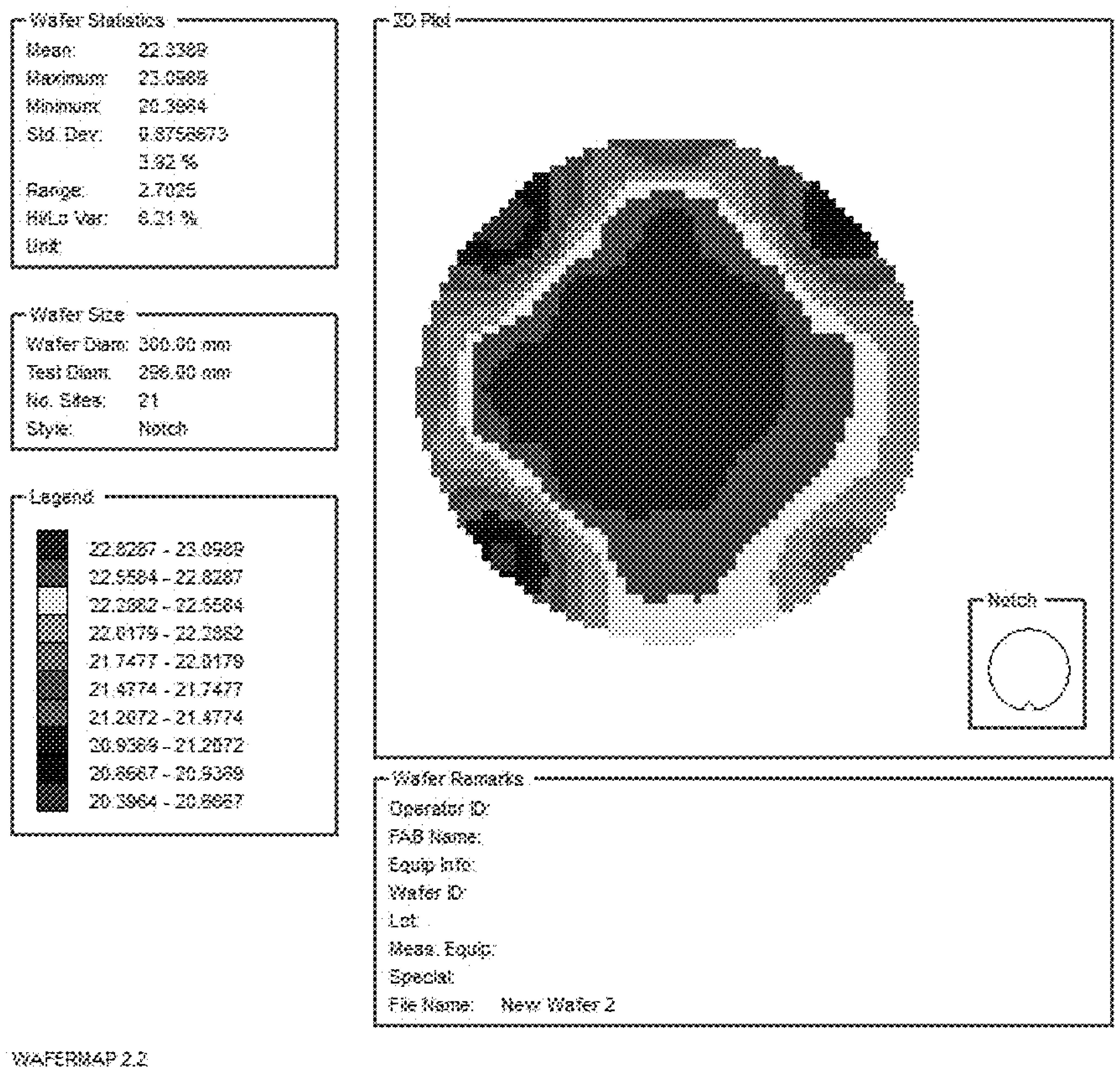
Test Diam: 298.00 mm
No. Sites: 21
Style: Notch
Legend
60.3809 - 62.2298
58.532 - 60.3809
56.6831 - 58.532
54.8342 - 56.6831
52.9853 - 54.8342
51.1364 - 52.9853
49.2875 - 51.1364
47.4386 - 49.2875
45.5897 - 47.4386
43.7408 - 45.5897
2D Plot
Notch
Wafer Remarks
Operator ID:
FAB Name:
Equip Info:
Wafer ID:
Lot:
Meas. Equip:
Special:
File Name: New Wafer 2
WAFERMAP 2.2

FIG. 3b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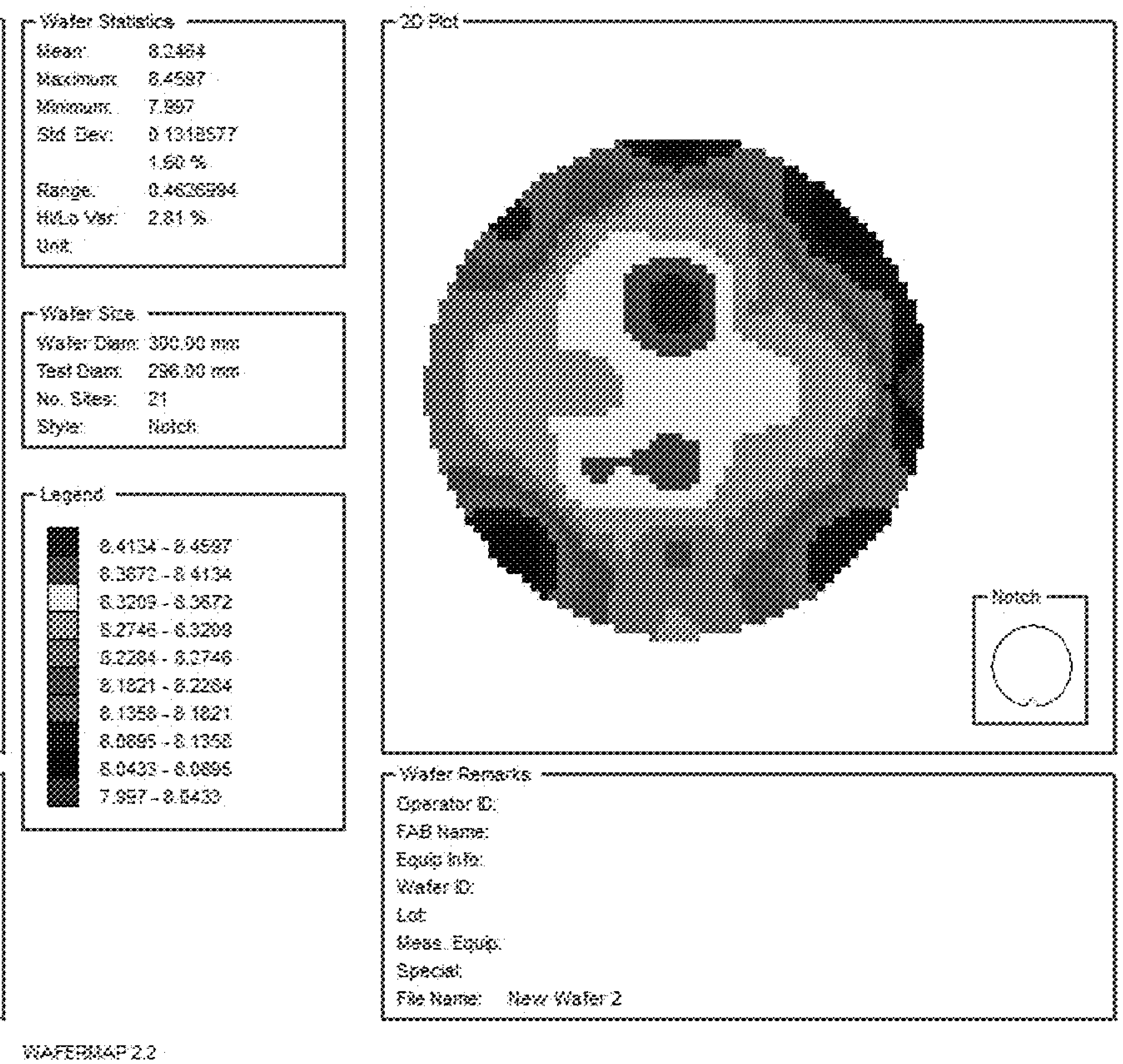
Maximum: 23.0988
Minimum: 20.3964
Std. Dev: 0.8756873
3.92 %
Range: 2.7025
Hi/Lo Var: 6.21 %
Unit:
Wafer Size
Wafer Diam: 300.00 mm
Test Diam: 296.00 mm
No. Sites: 21
Style: Notch
Legend
22.8287 - 23.0989
22.5584 - 22.8287
22.2882 - 22.5584
22.0179 - 22.2882
21.7477 - 22.0179
21.4774 - 21.7477
21.2072 - 21.4774
20.9369 - 21.2072
20.6667 - 20.9369
20.3964 - 20.6667
2D Plot
Notch
Wafer Remarks
Operator ID:
FAB Name:
Equip Info:
Wafer ID:
Lot:
Meas. Equip:
Special:
File Name: New Wafer 2
WAFERMAP 2.2

FIG. 4a


Wafer Statistics
Mean: 8.2464
Maximum: 8.4597
Minimum: 7.997
Std. Dev: 0.1318577
1.60 %
Range: 0.4626994
Hi/Lo Var: 2.81 %
Unit:
Wafer Size
Wafer Diam: 300.00 mm
Test Diam: 296.00 mm
No. Sites: 21
Style: Notch
Legend
8.4134 - 8.4597
8.3672 - 8.4134
8.3209 - 8.3672
8.2746 - 8.3209
8.2284 - 8.2746
8.1821 - 8.2284
8.1358 - 8.1821
8.0895 - 8.1358
8.0433 - 8.0895
7.997 - 8.0433
2D Plot
Notch
Wafer Remarks
Operator ID:
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Meas. Equip:
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WAFERMAP 2.2

FIG. 4b

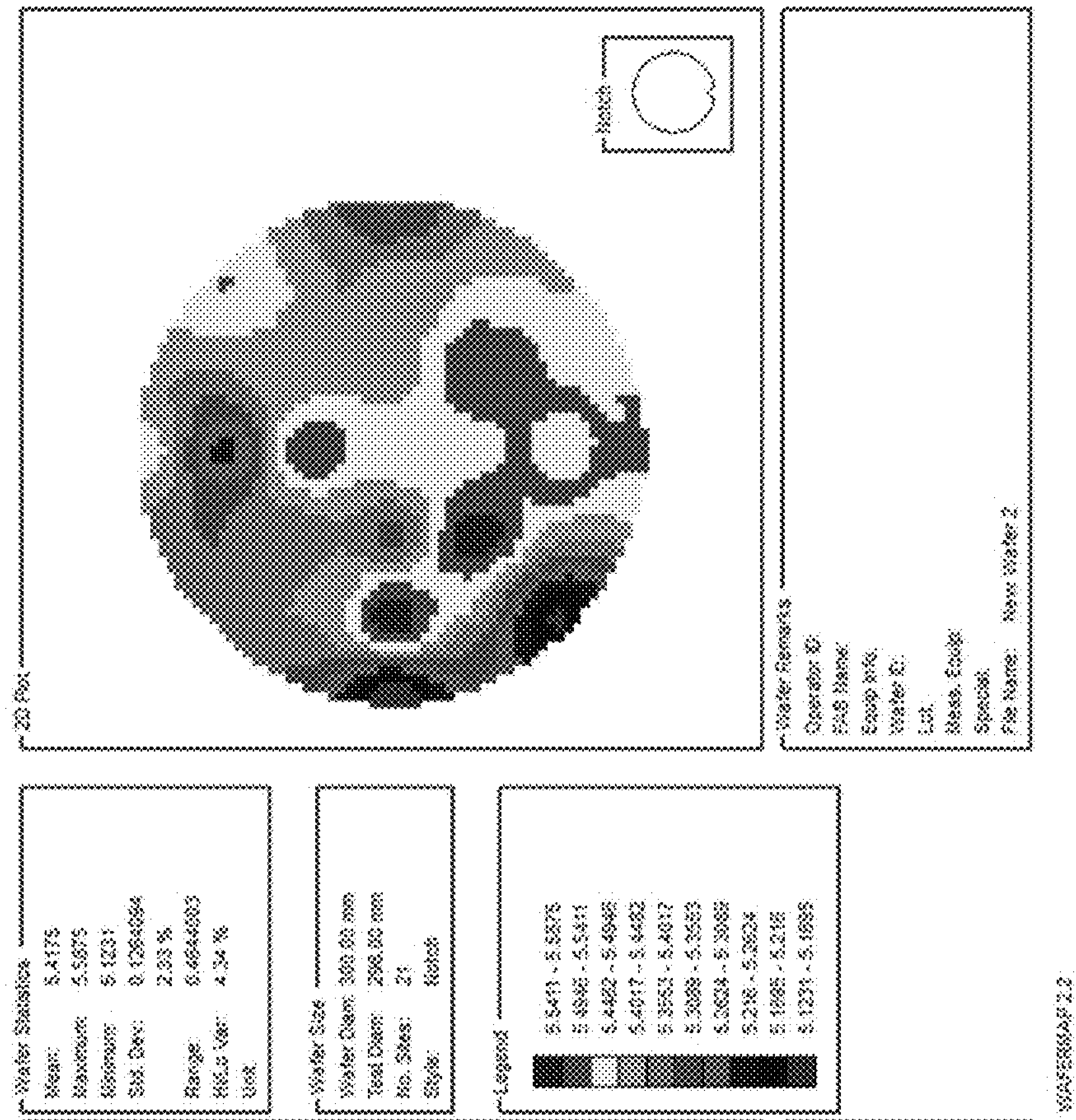

FIG. 5b

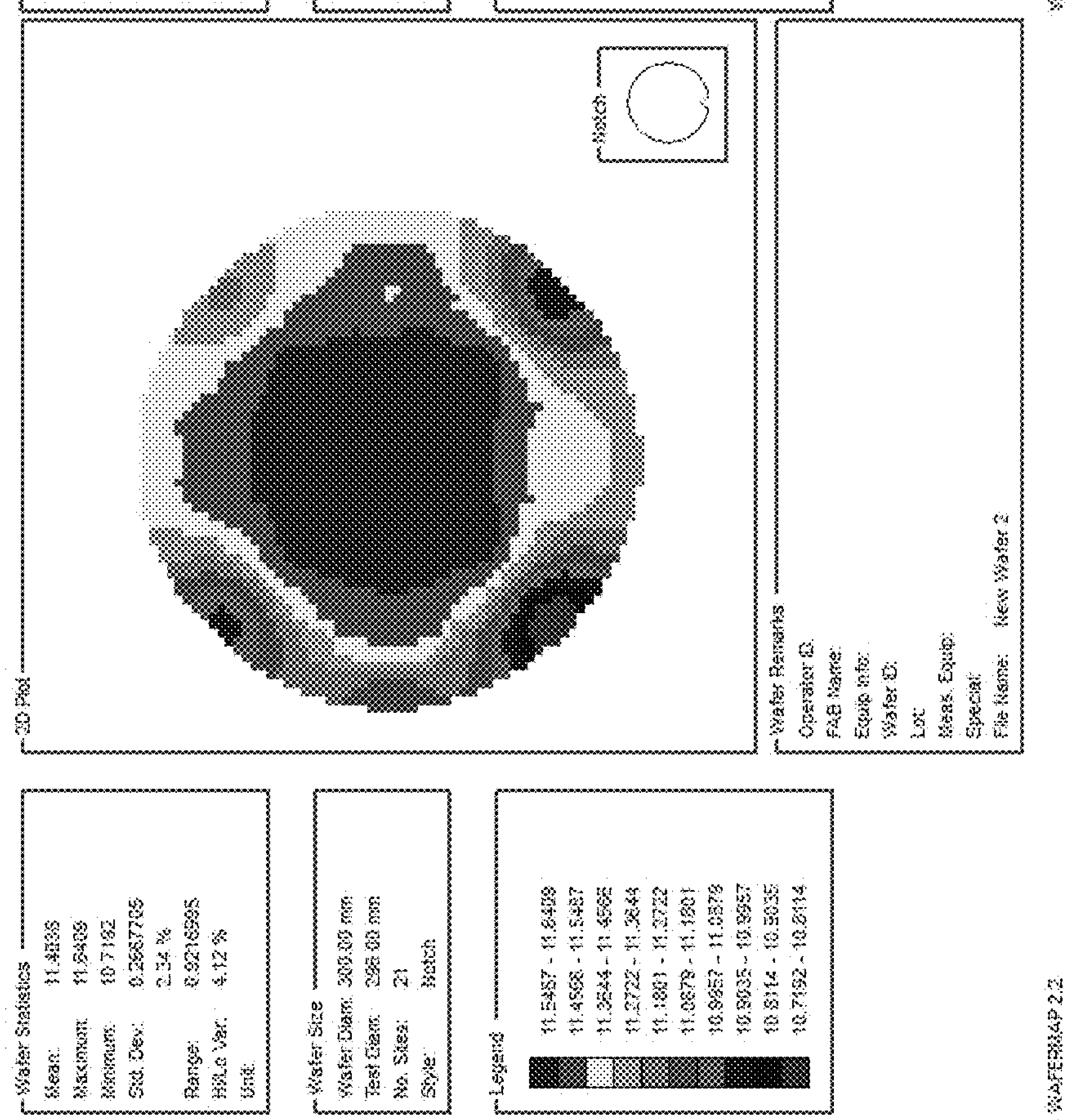

FIG. 5a

METHOD OF FORMING A STRUCTURE ON A SUBSTRATE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. patent application Ser. No. 15/388,410, filed on Dec. 22, 2016, and entitled "METHOD OF FORMING A STRUCTURE ON A SUBSTRATE," the disclosure of which is hereby incorporated by reference in its entirety.

FIELD OF INVENTION

The present disclosure generally relates to methods and systems for manufacturing electronic devices. More particularly, the disclosure relates to methods for providing a structure by depositing a layer on a substrate in a reactor.

BACKGROUND

As the trend has pushed structures in semiconductor devices to smaller and smaller sizes, different patterning techniques have arisen to produce these structures. These techniques include spacer defined double or quadruple patterning, (immersion) lithography (193i), extreme ultraviolet lithography (EUV), and directed self-assembly (DSA) lithography. Lithography may be combined with spacer defined double or quadruple patterning.

In these techniques it may be advantageous to transfer the pattern of the polymer resist to a hardmask. A hardmask is a material used in semiconductor processing as an etch mask with a good etching resistance and etching selectivity to produce small structures. The hardmask may be made from a silicon dioxide layer.

Spacers may also be used in semiconductor manufacturing to protect against subsequent processing steps and may be made from silicon dioxide.

Further silicon dioxide can be used to fill gaps in the structures of semiconductor devices.

It is therefore advantageous to produce a silicon dioxide layer.

SUMMARY

In accordance with at least one embodiment of the invention there is provided a method of providing a structure by depositing a layer on a substrate in a reactor, the method comprising:

introducing a silicon halide precursor in the reactor;

introducing a reactant gas comprising oxygen in the reactor; and,

providing an energy source to create a plasma from the reactant gas so that the oxygen reacts with the first precursor in the layer comprising silicon dioxide.

The reactant gas may comprise substantially no nitrogen. By using a reactant gas which is substantially nitrogen free a silicon dioxide layer may be deposited. The layer may have an improved etch rate. With substantially no nitrogen a nitrogen concentration of less than 5000 ppm, preferably less than 1000 ppm and most preferably less than 100 ppm nitrogen may be meant.

According to a further embodiment there is provided a method of providing a structure by depositing a layer on a substrate, the method comprising:

providing a silicon halide precursor in the reactor;

providing a reactant gas comprising oxygen in the reactor;

providing an energy source to create a plasma from the reactant gas so that the reactant gas reacts with the silicon halide precursor until the layer comprising silicon dioxide is formed.

For purposes of summarizing the invention and the advantages achieved over the prior art, certain objects and advantages of the invention have been described herein above. Of course, it is to be understood that not necessarily all such objects or advantages may be achieved in accordance with any particular embodiment of the invention. Thus, for example, those skilled in the art will recognize that the invention may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught or suggested herein without necessarily achieving other objects or advantages as may be taught or suggested herein.

All of these embodiments are intended to be within the scope of the invention herein disclosed. These and other embodiments will become readily apparent to those skilled in the art from the following detailed description of certain embodiments having reference to the attached figures, the invention not being limited to any particular embodiment(s) disclosed.

BRIEF DESCRIPTION OF THE FIGURES

These and other features, aspects, and advantages of the invention disclosed herein are described below with reference to the drawings of certain embodiments, which are intended to illustrate and not to limit the invention.

FIG. **1** is a flowchart in accordance with at least one embodiment of the invention.

FIGS. **2***a* and **2***b* shows a PECVD SiO2 layer formed at 550 C.° according to an embodiment before (**2***a*) and after (**2***b*) etching.

FIGS. **3***a* and **3***b* shows a PECVD SiO2 layer formed at 400 C.° according to an embodiment before (**3***a*) and after (**3***b*) etching.

FIGS. **4***a* and **4***b* shows a PEALD SiO2 layer formed at 550 C.° according to an embodiment before (**4***a*) and after (**4***b*) etching.

FIGS. **5***a* and **5***b* shows a PEALD SiO2 layer formed at 400 C.° according to an embodiment before (**5***a*) and after (**5***b*) etching.

It will be appreciated that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale to help improve understanding of illustrated embodiments of the present disclosure.

DETAILED DESCRIPTION

Although certain embodiments and examples are disclosed below, it will be understood by those in the art that the invention extends beyond the specifically disclosed embodiments and/or uses of the invention and obvious modifications and equivalents thereof. Thus, it is intended that the scope of the invention disclosed should not be limited by the particular disclosed embodiments described below.

The particular implementations shown and described are illustrative of the invention and its best mode and are not intended to otherwise limit the scope of the aspects and implementations in any way. Indeed, for the sake of brevity, conventional manufacturing, connection, preparation, and other functional aspects of the system may not be described in detail.

Silicon dioxide films have a wide variety of applications, as will be apparent to the skilled artisan, such as in planar logic, DRAM, and NAND Flash devices. More specifically, conformal silicon dioxide thin films that display uniform etch behavior have a wide variety of applications, both in the semiconductor industry and also outside of the semiconductor industry. According to some embodiments of the present disclosure, various silicon dioxide films and precursors and methods for depositing those films by atomic layer deposition (ALD) are provided. Importantly, in some embodiments the silicon dioxide films have a relatively uniform etch rate for both the vertical and the horizontal portions, when deposited onto 3-dimensional structures. Such three-dimensional structures may include, for example and without limitation, FinFETs or other types of multiple gate FETs.

Thin film layers comprising silicon oxide can be deposited by plasma-enhanced atomic layer deposition (PEALD) or chemical vapor deposition (PECVD) type processes or by thermal ALD processes. In some embodiments a silicon oxide thin film is deposited over a three dimensional structure, such as a fin in the formation of a FinFET device, and/or in the application of spacer defined double patterning (SDDP) and/or spacer defined quadruple patterning (SDQP). In some embodiments a silicon oxide thin film is deposited over a flat layer as a hard mask and subsequent layer are positioned on top for lithographic processing.

The formula of the silicon dioxide is generally referred to herein as SiO_2 for convenience and simplicity. However, the skilled artisan will understand that the Si:O ratio in the silicon dioxide layer and excluding hydrogen or other impurities, can be represented as SiOx, where x varies from about 0.5 to about 2.0, as long as some Si—O bonds are formed. In some cases, x may vary from about 0.9 to about 1.7, from about 1.0 to about 1.5, or from about 1.2 to about 1.4. In some embodiments unstable silicon monoxide is formed which may decompose in Si and SiO_2.

ALD-type processes are based on controlled, generally self-limiting surface reactions. Gas phase reactions are typically avoided by contacting the substrate alternately and sequentially with the reactants. Vapor phase reactants are separated from each other in the reaction chamber, for example, by removing excess reactants and/or reactant byproducts between reactant pulses. The reactants may be removed from proximity with the substrate surface with the aid of a purge gas and/or vacuum. In some embodiments excess reactants and/or reactant byproducts are removed from the reaction space by purging, for example with an inert gas.

The methods presented herein provide for deposition of SiO_2 thin films on substrate surfaces. Geometrically challenging applications are also possible due to the nature of ALD-type processes. According to some embodiments, ALD-type processes are used to form SiO_2 thin films on substrates such as integrated circuit workpieces, and in some embodiments on three-dimensional structures on the substrates. In some embodiments, ALD type processes comprise alternate and sequential contact of the substrate with a silicon halide precursor and an oxygen precursor. In some embodiments, a silicon precursor contacts the substrate such silicon species adsorb onto the surface of the substrate. In some embodiments, the silicon species may be same as the silicon precursor, or may be modified in the adsorbing step, such as by losing one or more ligands.

According to certain embodiments, a silicon dioxide thin film may be formed on a substrate by an ALD-type process comprising multiple silicon dioxide deposition cycles, each silicon dioxide deposition cycle comprising:

(1) contacting a substrate with a first silicon precursor, preferably a silicon halide such that the silicon species adsorb on the substrate surface;

(2) contacting the substrate with an oxygen comprising reactant gas; and

(3) repeating steps (1) and (2) as many times as required or desired to achieve a thin film of a desired thickness and composition. Excess reactants may be removed from the vicinity of the substrate, for example by purging from the reaction space with an inert gas, after each contacting step.

PEALD Processes

In some embodiments, plasma enhanced ALD (PEALD) processes are used to deposit silicon dioxide films. Briefly, a substrate or workpiece is placed in a reaction chamber and subjected to alternately repeated surface reactions. In some embodiments, thin silicon dioxide films are formed by repetition of a self-limiting ALD cycle. Preferably, for forming silicon dioxide films, each ALD cycle comprises at least two distinct phases. The provision and removal of a reactant from the reaction space may be considered a phase. In a first phase, a first reactant comprising silicon is provided and forms no more than about one monolayer on the substrate surface. This reactant is also referred to herein as "the silicon precursor," "silicon-containing precursor," or "silicon reactant" and may be, for example, a silicon halide such as H_2SiI_2.

In a second phase, a (second) reactant comprising a reactive species is provided and may convert adsorbed silicon species to silicon dioxide. In some embodiments the reactant gas comprises an oxygen precursor. In some embodiments, the reactive species comprises an excited species. In some embodiments the reactant comprises a species from an oxygen containing plasma. In some embodiments, the reactant comprises oxygen radicals, oxygen atoms and/or oxygen plasma. In some embodiments, the reactant may comprise O-containing plasma or a plasma comprising O. In some embodiments, the reactant may comprise a plasma comprising O-containing species. In some embodiments the reactant may comprise oxygen atoms and/or O* radicals. The reactant gas may comprise other species that are not oxygen precursors. In some embodiments, the reactant may comprise a plasma of argon, radicals of argon, or atomic argon in one form or another. In some embodiments, the reactant may comprise a species from a noble gas, such as He, Ne, Ar, Kr, or Xe, preferably Ar or He, for example as radicals, in plasma form, or in elemental form. These reactive species from noble gases do not necessarily contribute material to the deposited film, but can in some circumstances contribute to film growth as well as help in the formation and ignition of plasma. In some embodiments a gas that is used to form a plasma may flow constantly throughout the deposition process but only be activated intermittently. In some embodiments, the reactant does not comprise a species from a noble gas, such as Ar. Thus, in some embodiments the adsorbed silicon halide precursor is not contacted with a reactive species generated by a plasma from Ar.

Additional phases may be added and phases may be removed as desired to adjust the composition of the final film.

One or more of the reactants may be provided with the aid of a carrier gas, such as for example Ar or He. In some embodiments the silicon halide precursor and the reactant are provided with the aid of a carrier gas.

In some embodiments, two of the phases may overlap, or be combined. For example, the silicon halide precursor and the reactant may be provided simultaneously in pulses that partially or completely overlap. In addition, although referred to as the first and second phases, and the first and second reactants, the order of the phases may be varied, and an ALD cycle may begin with any one of the phases. That is, unless specified otherwise, the precursors and reactants can be provided in any order, and the process may begin with any of the precursors or reactant.

As discussed in more detail below, in some embodiments for depositing a silicon dioxide film, one or more deposition cycles begin with provision of the silicon halide precursor, followed by the reactant. In other embodiments deposition may begin with provision of the reactant, followed by the silicon halide precursor.

In some embodiments the substrate on which deposition is desired, such as a semiconductor workpiece, is loaded into a reactor. The reactor may be part of a cluster tool in which a variety of different processes in the formation of an integrated circuit are carried out. In some embodiments a flow-type reactor is utilized. In some embodiments a shower head type of reactor is utilized. In some embodiments, a space divided reactor is utilized. In some embodiments a high-volume manufacturing-capable single wafer ALD reactor is used. In other embodiments a batch reactor comprising multiple substrates is used. For embodiments in which batch ALD reactors are used, the number of substrates is preferably in the range of 10 to 200, more preferably in the range of 50 to 150, and most preferably in the range of 100 to 130.

Exemplary single wafer reactors, designed specifically to enhance ALD processes, are commercially available from ASM America, Inc. (Phoenix, Ariz.) under the tradenames Pulsar® 2000 and Pulsar® 3000 and ASM Japan K.K (Tokyo, Japan) under the tradename Eagle® XP, XP8 and Dragon®. Exemplary batch ALD reactors, designed specifically to enhance ALD processes, are commercially available from and ASM Europe B.V (Almere, Netherlands) under the tradenames A400™ and A412™.

In some embodiments, if necessary, the exposed surfaces of the workpiece can be pretreated to provide reactive sites to react with the first phase of the ALD process. In some embodiments a separate pretreatment step is not required. In some embodiments the substrate is pretreated to provide a desired surface termination. In some embodiments the substrate is pretreated with plasma.

Excess reactant and reaction byproducts, if any, are removed from the vicinity of the substrate, and in particular from the substrate surface, between reactant pulses. In some embodiments the reaction chamber is purged between reactant pulses, such as by purging with an inert gas. The flow rate and time of each reactant, is tunable, as is the removal step, allowing for control of the quality and various properties of the films.

As mentioned above, in some embodiments a reaction gas is provided to the reaction chamber continuously during each deposition cycle, or during the entire ALD process, and reactive species are provided by generating a plasma in the reaction gas, either in the reaction chamber or upstream of the reaction chamber. In some embodiments the reaction gas comprises oxygen. In some embodiments the reaction gas is oxygen. In other embodiments the reactant gas may comprise helium, or argon. In some embodiments the reactant gas is helium or argon. The reactant gas such as oxygen, argon, helium or argon may have a flow of 0.1 to 10, preferably 2 to 8, more preferably 3 to 6 and most preferably around 5 slm. The gas may also serve as a purge gas for the precursor and/or reactant (or reactive species).

In some embodiments, nitrogen, argon, or helium may serve as a purge gas for a first precursor and a source of excited species for converting the silicon halide precursor to the silicon dioxide film.

The cycle is repeated until a film of the desired thickness and composition is obtained. In some embodiments the deposition parameters, such as the flow rate, flow time, purge time, and/or reactants themselves, may be varied in one or more deposition cycles during the ALD process in order to obtain a film with the desired characteristics. In some embodiments, argon and/or argon plasma are not provided in a deposition cycle, or in the deposition process.

The term "pulse" may be understood to comprise feeding reactant into the reaction chamber for a predetermined amount of time. The term "pulse" does not restrict the length or duration of the pulse and a pulse can be any length of time.

In some embodiments, the silicon reactant is provided first. After an initial surface termination, if necessary or desired, a first silicon reactant pulse is supplied to the workpiece. In accordance with some embodiments, the first reactant pulse comprises a carrier gas flow and a volatile silicon species, for example a silicon halide such as H_2SiI_2, that is reactive with the workpiece surfaces of interest. Accordingly, the silicon reactant adsorbs upon these workpiece surfaces. The first reactant pulse self-saturates the workpiece surfaces such that any excess constituents of the first reactant pulse do not further react with the molecular layer formed by this process. The carrier gas may have a flow of 0.5 to 8, preferably 1 to 5, more preferably 2 to 3 and most preferably around 2.8 slm.

The first silicon reactant pulse is preferably supplied in gaseous form. The silicon precursor gas is considered "volatile" for purposes of the present description if the species exhibits sufficient vapor pressure under the process conditions to transport the species to the workpiece in sufficient concentration to saturate exposed surfaces.

In some embodiments the silicon reactant pulse is from about 0.05 seconds to about 5.0 seconds, about 0.1 seconds to about 3 seconds or about 0.2 seconds to about 1.0 seconds. The optimum pulsing time can be readily determined by the skilled artisan based on the particular circumstances.

In some embodiments the silicon reactant consumption rate is selected to provide a desired dose of precursor to the reaction space. Reactant consumption refers to the amount of reactant consumed from the reactant source, such as a reactant source bottle, and can be determined by weighing the reactant source before and after a certain number of deposition cycles and dividing the mass difference by the number of cycles. In some embodiments the silicon reactant consumption is more than about 0.1 mg/cycle. In some embodiments the silicon reactant consumption is about 0.1 mg/cycle to about 50 mg/cycle, about 0.5 mg/cycle to about 30 mg/cycle or about 2 mg/cycle to about 20 mg/cycle. In some embodiments the minimum preferred silicon reactant consumption may be at least partly defined by the reactor dimensions, such as the heated surface area of the reactor. In some embodiments in a showerhead reactor designed for 300 mm silicon wafers, silicon reactant consumption is more than about 0.5 mg/cycle, or more than about 2.0 mg/cycle. In some embodiments the silicon reactant consumption is more than about 5 mg/cycle in a showerhead reactor designed for 300 mm silicon wafers. In some embodiments the silicon reactant consumption is more than about 1 mg/cycle, preferably more than 5 mg/cycle at reaction temperatures below about 550° C. in a showerhead reactor designed for 300 mm silicon wafers.

After sufficient time for a molecular layer to adsorb on the substrate surface, excess first silicon reactant is then removed from the reaction space. In some embodiments the excess first reactant is purged by stopping the flow of the first chemistry while continuing to flow a carrier gas or purge gas for a sufficient time to diffuse or purge excess reactants and reactant by-products, if any, from the reaction space. In some embodiments the excess first precursor is purged with the aid of inert gas, such as argon, that is flowing throughout the ALD cycle.

In some embodiments, the first reactant is purged for about 0.1 seconds to about 10 seconds, about 0.3 seconds to about 5 seconds or about 0.3 seconds to about 1 second. Provision and removal of the silicon reactant can be considered the first or silicon phase of the ALD cycle.

In the second phase, a reactant comprising a reactive species, such as oxygen plasma is provided to the workpiece. Argon, Ar, is flowed continuously to the reaction chamber during each ALD cycle in some embodiments. Argon plasma may be formed by generating a plasma in argon in the reaction chamber or upstream of the reaction chamber, for example by flowing the argon through a remote plasma generator.

In some embodiments, plasma is generated upon flowing oxygen and argon gases. In some embodiments the Ar and O_2 are provided to the reaction chamber before the plasma is ignited or oxygen and Ar ions or radicals are formed. In some embodiments the Ar and O_2 are provided to the reaction chamber continuously and oxygen and Ar containing plasma, ions or radicals is created or supplied when needed.

Typically, the reactant, for example comprising oxygen plasma, is provided for about 0.1 seconds to about 10 seconds. In some embodiments the reactant, such as oxygen plasma, is provided for about 0.1 seconds to about 10 seconds, 0.5 seconds to about 5 seconds or 0.5 seconds to about 2.0 seconds. However, depending on the reactor type, substrate type and its surface area, the reactant pulsing time may be even higher than about 10 seconds. In some embodiments, pulsing times can be on the order of minutes. The optimum pulsing time can be readily determined by the skilled artisan based on the particular circumstances.

In some embodiments the reactant is provided in two or more distinct pulses, without introducing another reactant in between any of the two or more pulses. For example, in some embodiments an oxygen plasma is provided in two or more, preferably in two, sequential pulses, without introducing a Si-precursor in between the sequential pulses. In some embodiments during provision of oxygen plasma two or more sequential plasma pulses are generated by providing a plasma discharge for a first period of time, extinguishing the plasma discharge for a second period of time, for example from about 0.1 seconds to about 10 seconds, from about 0.5 seconds to about 5 seconds or about 1.0 seconds to about 4.0 seconds, and exciting it again for a third period of time before introduction of another precursor or a removal step, such as before the Si-precursor or a purge step. Additional pulses of plasma can be introduced in the same way. In some embodiments a plasma is ignited for an equivalent period of time in each of the pulses.

Oxygen plasma may be generated by applying RF power of from about 10 W to about 2000 W, preferably from about 50 W to about 1000 W, more preferably from about 100 W to about 600 W in some embodiments. In some embodiments the RF power density may be from about 0.02 W/cm^2 to about 2.0 W/cm^2, preferably from about 0.05 W/cm^2 to about 1.5 W/cm^2. The RF power may be applied to oxygen that flows during the oxygen plasma pulse time, that flows continuously through the reaction chamber, and/or that flows through a remote plasma generator. Thus in some embodiments the plasma is generated in situ, while in other embodiments the plasma is generated remotely. In some embodiments a showerhead reactor is utilized and plasma is generated between a substrate holder (on top of which the substrate is located) and a showerhead plate. In some embodiments the gap between the substrate holder and showerhead plate is from about 0.1 cm to about 20 cm, from about 0.5 cm to about 5 cm, or from about 0.8 cm to about 3.0 cm.

After a time period sufficient to completely saturate and react the previously adsorbed molecular layer with the oxygen plasma pulse, any excess reactant and reaction byproducts are removed from the reaction space. As with the removal of the first reactant, this step may comprise stopping the generation of reactive species and continuing to flow the inert gas, such as helium or argon for a time period sufficient for excess reactive species and volatile reaction by-products to diffuse out of and be purged from the reaction space. In other embodiments a separate purge gas may be used. The purge may, in some embodiments, be from about 0.1 seconds to about 10 seconds, about 0.1 seconds to about 4 seconds or about 0.1 seconds to about 0.5 seconds. Together, the oxygen plasma provision and removal represent a second, reactive species phase in a silicon dioxide atomic layer deposition cycle.

The two phases together represent one ALD cycle, which is repeated to form silicon dioxide thin films of a desired thickness. While the ALD cycle is generally referred to herein as beginning with the silicon phase, it is contemplated that in other embodiments the cycle may begin with the reactive species phase. One of skill in the art will recognize that the first precursor phase generally reacts with the termination left by the last phase in the previous cycle. Thus, while no reactant may be previously adsorbed on the substrate surface or present in the reaction space if the reactive species phase is the first phase in the first ALD cycle, in subsequent cycles the reactive species phase will effectively follow the silicon phase. In some embodiments one or more different ALD cycles are provided in the deposition process.

According to some embodiments of the present disclosure, PEALD reactions may be performed at temperatures ranging from about 25° C. to about 700° C., preferably from about 50° C. to about 600° C., more preferably from about 100° C. to about 450° C., and most preferably from about 200° C. to about 400° C. In some embodiments, the optimum reactor temperature may be limited by the maximum allowed thermal budget. Therefore, in some embodiments the reaction temperature is from about 300° C. to about 400° C. In some applications, the maximum temperature is around about 400° C., and, therefore the PEALD process is run at that reaction temperature.

According to some embodiments of the present disclosure, the pressure of the reaction chamber during processing is maintained between 0.08 to 40 Torr, preferably 0.8 to 30 Torr and more preferably between 2 to 20 Torr, and most preferably around 8 Torr.

PECVD Process

Plasma-enhanced chemical vapor deposition (PECVD) is a process used to deposit thin films from a gas state (vapor) to a solid state on a substrate. Chemical reactions are involved in the process, which occur after creation of a plasma of the reactive gases. The plasma is continuously applied to the space between which is filled with the reactive gases. In some embodiments, a radio frequency (RF) plasma source is employed to create the plasma, though any type of plasma source capable of generating a direct plasma may be employed, including microwave and DC sources. Further, in some embodiments, a remotely-generated plasma may be employed to supply reactive species. In further embodiments (pulse PECVD) only one of the reactants, either the Silicon precursor or the reactive species is provided continuously to the chamber while the other reactant is pulsed intermittently

Si Precursors

A number of suitable silicon halide precursors can be used in the presently disclosed PEALD processes. At least some of the suitable precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nX_yA_z \quad (1)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z), z=0 or more (and up to 2n+2−y), X is I or Br, and A is a halogen other than X, preferably n=1-5 and more preferably n=1-3 and most preferably 1-2.

According to some embodiments, silicon halide precursors may comprise one or more cyclic compounds. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nX_yA_z \quad (2)$$

wherein the formula (2) compound is cyclic compound, n=3-10, y=1 or more (and up to 2n−z), z=0 or more (and up to 2n−y), X is I or Br, and A is a halogen other than X, preferably n=3-6.

According to some embodiments, silicon halide precursors may comprise one or more iodosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nI_yA_z \quad (3)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z), z=0 or more (and up to 2n+2−y), and A is a halogen other than I, preferably n=1-5 and more preferably n=1-3 and most preferably 1-2.

According to some embodiments, some silicon halide precursors may comprise one or more cyclic iodosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nI_yA_z \quad (4)$$

wherein the formula (4) compound is a cyclic compound, n=3-10, y=1 or more (and up to 2n−z), z=0 or more (and up to 2n−y), and A is a halogen other than I, preferably n=3-6.

According to some embodiments, some silicon halide precursors may comprise one or more bromosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nBr_yA_z \quad (5)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z), z=0 or more (and up to 2n+2−y), and A is a halogen other than Br, preferably n=1-5 and more preferably n=1-3 and most preferably 1-2.

According to some embodiments, some silicon halide precursors may comprise one or more cyclic bromosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nBr_yA_z \quad (6)$$

wherein the formula (6) compound is a cyclic compound, n=3-10, y=1 or more (and up to 2n−z), z=0 or more (and up to 2n−y), and A is a halogen other than Br, preferably n=3-6.

According to some embodiments, preferred silicon precursors comprise one or more iodosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nI_y \quad (7)$$

wherein, n=1-5, y=1 or more (up to 2n+2), preferably n=1-3 and more preferably n=1-2.

According to some embodiments, preferred silicon halide precursors comprise one or more bromosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z}Si_nI_y \quad (8)$$

wherein, n=1-5, y=1 or more (up to 2n+2), preferably n=1-3 and more preferably n=1-2.

According to some embodiments of a PEALD process, suitable silicon halide precursors can include at least compounds having any one of the general formulas (1) through (8). In general formulas (1) through (8), halides/halogens can include F, Cl, Br and I. In some embodiments, a silicon halide precursor comprises SiI_4, $HSiI_3$, H_2SiI_2, H_3SiI, Si_2I_6, HSi_2I_5, $H_2Si_2I_4$, $H_3Si_2I_3$, $H_4Si_2I_2$, H_5Si_2I, or Si_3I_8. In some embodiments, a silicon halide precursor comprises one of $HSiI_3$, H_2SiI_2, H_3SiI, $H_2Si_2I_4$, $H_4Si_2I_2$, and H_5Si_2I. In some embodiments the silicon halide precursor comprises two, three, four, five or six of $HSiI_3$, H_2SiI_2, H_3SiI, $H_2Si_2I_4$, $H_4Si_2I_2$, and H_5Si_2I, including any combinations thereof.

In certain embodiments, the Si halide precursor is H_2SiI_2. In some embodiments, Si halide precursors of formulas (9)-(28), below, can be used in PEALD processes.

O-Precursors

As discussed above, the reactant according to the present disclosure may comprise an oxygen precursor. In some embodiments the reactant in a PEALD process may comprise a reactive species. Suitable plasma compositions include oxygen plasma, radicals of oxygen, or atomic oxygen in one form or another. In some embodiments, the reactive species may comprise O-containing plasma or a plasma comprising O. In some embodiments, the reactive species may comprise a plasma comprising O-containing species. In some embodiments the reactive species may comprise oxygen atoms and/or O* radicals. In some embodiments, argon plasma, radicals of argon, or atomic argon in one form or another are also provided. And in some embodiments, a plasma may also contain noble gases, such as He, Ne, Ar, Kr and Xe, preferably Ar or He, in plasma form, as radicals, or in atomic form. In some embodiments, the reactant does not comprise any species from a noble gas, such as Ar. Thus, in some embodiments plasma is not generated in a gas comprising a noble gas.

In some embodiments the reactant may be formed, at least in part, from O_2 and H_2, where the O_2 and H_2 are provided at a flow ratio (O_2/H_2) from about 20:1 to about 1:20, preferably from about 10:1 to about 1:10, more preferably from about 5:1 to about 1:5 more preferably from about 1:2 to about 4:1, and most preferably 1:1.

The reactant may be formed in some embodiments remotely via plasma discharge ("remote plasma") away from the substrate or reaction space. In some embodiments, the reactant may be formed in the vicinity of the substrate or directly above substrate ("direct plasma).

FIG. **1** is a flow chart generally illustrating a depositing a layer on a substrate in a reactor in accordance with some embodiments. According to certain embodiment, the process may comprise the following:

(1) a substrate comprising a three-dimensional structure is provided in a reaction space;

(2) a silicon-containing precursor, such as SiI2H2, is introduced into the reaction space so that silicon-containing species are adsorbed to a surface of the substrate;

(3) excess silicon-containing precursor and reaction byproducts may be substantially removed from the reaction space;

(4) an oxygen comprising reactant, such as O_2, H_2O, H_2O_2, is introduced into the reaction chamber, and reactive species from the oxygen are created and the reactive species are contacted with the substrate; and

(5) removing excess oxygen atoms, plasma, or radicals and reaction byproducts;

Steps (2) through (5) of the silicon dioxide deposition cycle (7) may be repeated (6) until a silicon dioxide film of a desired thickness is formed. The temperature of the substrate may be between 25 to 700° C., preferably between 100 and 650° C., more preferably between 200 and 625° C., most preferably between 300 and 600° C. and even more preferable around 400° C. during providing a reactant gas and providing an energy source to create the plasma.

Oxygen may flow continuously throughout the silicon dioxide deposition cycle, with oxygen plasma formed at the appropriate times to convert adsorbed silicon compound into silicon dioxide.

As mentioned above, in some embodiments the substrate may be contacted simultaneously with the silicon compound and the reactive oxygen species to form the layer in a plasma enhanced chemical vapor deposition (PECVD) process.

According to some embodiments, the silicon dioxide layer is deposited using a plasma enhanced chemical vapor deposition (PEALD) process on a substrate having three-dimensional features, such as in a FinFET application. The features may have an aspect ratios of more than 2, preferably an aspect ratios of more than 3, more preferably an aspect ratios of more than 6 and most preferably an aspect ratios of more than 11. The process may comprise the steps as described above in conjunction with FIG. **1**.

Si Precursors

A number of suitable silicon halide precursors may be used in the presently disclosed processes. In some embodiments these precursors may be used in plasma ALD or plasma CVD processes thereby a layer with a desired quality (at least one of the desired WER, WERR, pattern loading effect or/and step coverage features described below) is deposited.

According to some embodiments, some silicon precursors comprise iodine or bromine and the film deposited by using that precursor has at least one desired property, for example at least one of the desired WER, WERR, pattern loading effect or/and step coverage features described below.

At least some of the suitable precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_nX_yA_zR_w \quad (9)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=0 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more cyclic compounds. Such precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_nI_yA_zR_w \quad (10)$$

wherein, n=3-10, y=1 or more (and up to 2n−z−w), z=0 or more (and up to 2n−y−w), w=0 or more (and up to 2n−y−z), X is I or Br, A is a halogen other than X, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=3-6. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more iodosilanes. Such precursors may have the following general formula:

$$H_{2n-y-z-w}Si_nI_yA_zR_w \quad (11)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=0 or more (and up to 2n+2−y−z), A is a halogen other than I, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more cyclic iodosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_nI_yA_zR_w \quad (12)$$

wherein, n=3-10, y=1 or more (and up to 2n−z−w), z=0 or more (and up to 2n−y−w), w=0 or more (and up to 2n−y−z), A is a halogen other than I, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=3-6. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more bromosilanes. Such precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_nBr_yA_zR_w \quad (13)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=0 or more (and up to 2n+2−y−z), A is a halogen other than Br, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more cyclic bromosilanes. Such precursors may have the following general formula:

$$H_{2n-y-z-w}Si_nBr_yA_zR_w \quad (14)$$

wherein, n=3-10, y=1 or more (and up to 2n−z−w), z=0 or more (and up to 2n−y−w), w=0 or more (and up to 2n−y−z), A is a halogen other than Br, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=3-6. Preferably R is a C_1-C_3 alkyl ligand such as methyl, ethyl, n-propyl or isopropyl.

According to some embodiments, some silicon halide precursors comprise one or more iodosilanes or bromosilanes in which the iodine or bromine is not bonded to the silicon in the compound. Accordingly some suitable compounds may have iodine/bromine substituted alkyl groups. Such precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_nX_yA_zR^{II}_w \quad (15)$$

wherein, n=1-10, y=0 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=1 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, R^{II} is an organic ligand containing I or Br and can be independently selected from the group consisting of I or Br substituted alkoxides, alkylsilyls, alkyls, alkylamines and unsaturated hydrocarbons; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R^{II} is an iodine substituted C_1-C_3 alkyl ligand.

According to some embodiments, some silicon halide precursors comprise one or more cyclic iodosilanes or bromosilanes. Accordingly some suitable cyclic compounds may have iodine/bromine substituted alkyl groups. Such precursors may have the following general formula:

$$H_{2n-y-z-w}Si_nX_yA_zR^{II}_w \quad (16)$$

wherein, n=3-10, y=0 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=1 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, R^{II} is an organic ligand containing I or Br and can be independently selected from the group consisting of I or Br substituted alkoxides, alkylsilyls, alkyls, alkylamines and unsaturated hydrocarbons; preferably n=3-6. Preferably R is an iodine substituted C_1-C_3 alkyl ligand.

According to some embodiments, some suitable silicon halide precursors may have at least one of the following general formulas:

$$H_{2n+2-y-z-w}Si_nX_yA_z(NR_1R_2) \quad (17)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=1 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, N is nitrogen. and R_1 and R_2 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 and R_2 are hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl and n-butyl. More preferably R_1 and R_2 are hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl or isopropyl. Each of the $(NR1R_2)_w$ ligands can be independently selected from each other.

$$(H_{3-y-z-w}X_yA_z(NR_1R_2)_wSi)_3\text{—}N \quad (18)$$

wherein, y=1 or more (and up to 3−z−w), z=0 or more (and up to 3−y−w), w=1 or more (and up to 3−y−z), X is I or Br, A is a halogen other than X, N is nitrogen and R_1 and R_2 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon. Preferably R_1 and R_2 are hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl and n-butyl. More preferably R_1 and R_2 are hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl or isopropyl. Each of the (NR_1R_2), ligands can be independently selected from each other. Each of the three $H_{3-y-z-w}X_yA_z(NR_1R_2)_wSi$ ligands can be independently selected from each other.

In some embodiments, some suitable silicon halide precursors may have at least one of the following more specific formulas:

$$H_{2n+2-y-w}Si_nI_y(NR_1R_2)_w \quad (19)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−w), w=1 or more (and up to 2n+2−y), N is nitrogen, and R_1 and R_2 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 and R_2 are hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl and n-butyl. More preferably R_1 and R_2 are hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl or isopropyl. Each of the $(NR_1R_2)_w$ ligands can be independently selected from each other.

$$(H_{3-y-w}I_y(NR_1R_2)_wSi)_3\text{—}N \quad (20)$$

wherein, y=1 or more (and up to 3−w), w=1 or more (and up to 3−y), N is nitrogen and R_1 and R_2 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon. Preferably R_1 and R_2 are hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl and n-butyl. More preferably R_1 and R_2 are hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl or isopropyl. Each of the three $H_{3-y-w}I_y(NR_1R_2)_wSi$ ligands can be independently selected from each other.

According to some embodiments, some suitable silicon halide precursors may have at least one of the following general formulas:

$$H_{2n+2-y-z-w}Si_nX_yA_z(NR_1R_2)_w \quad (21)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=1 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, N is nitrogen, R_1 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon, and R_2 can be independently selected from the group consisting of alkyl, substituted alkyl, silyl, alkylsilyl and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 is hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_1 is hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Preferably R_2 is C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_2 is C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Each of the $(NR_1R_2)_w$ ligands can be independently selected from each other.

$$(H_{3-y-z-w}X_yA_z(NR_1R_2)_wSi)_3\text{—}N \quad (22)$$

wherein, y=1 or more (and up to 3−z−w), z=0 or more (and up to 3−y−w), w=1 or more (and up to 3−y−z), X is I or Br, A is a halogen other than X, N is nitrogen, R_1 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon, and R_2 can be independently selected from the group consisting of alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 is hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_1 is hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Preferably R_2 is C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_2 is C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Each of the $(NR_1R_2)_w$ ligands can be independently selected from each other.

In some embodiments, some suitable silicon halide precursors may have at least one of the following more specific formulas:

$$H_{2n+y-y-w}Si_nI_y(NR_1R_2)_w \qquad (23)$$

wherein, n=1-10, y=1 or more (and up to 2n+2−w), w=1 or more (and up to 2n+2−y), N is nitrogen, R_1 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon, and R_2 can be independently selected from the group consisting of alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 is hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_1 is hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Preferably R_2 is C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_2 is C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Each of the $(NR_1R_2)_w$ ligands can be independently selected from each other.

$$(H_{3-y-w}I_y(NR_1R_2)_wSi)_3\text{—}N \qquad (24)$$

wherein, y=1 or more (and up to 3−w), w=1 or more (and up to 3−y), N is nitrogen, R_1 can be independently selected from the group consisting of hydrogen, alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon, and R_2 can be independently selected from the group consisting of alkyl, substituted alkyl, silyl, alkylsilyl, and unsaturated hydrocarbon; preferably n=1-5 and more preferably n=1-3 and most preferably 1-2. Preferably R_1 is hydrogen or C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_1 is hydrogen or C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Preferably R_2 is C_1-C_4 alkyl groups, such as methyl, ethyl, n-propyl, isopropyl, t-butyl, isobutyl, sec-butyl, and n-butyl. More preferably R_2 is C_1-C_3 alkyl groups, such as methyl, ethyl, n-propyl, or isopropyl. Each of the $(NR_1R_2)_w$ ligands can be independently selected from each other.

According to some embodiments of a thermal ALD process, suitable silicon halide precursors can include at least compounds having any one of the general formulas (9) through (24). In general formulas (9) through (18) as well as in general formulas (21) and (22), halides/halogens can include F, Cl, Br and I.

In some embodiments, a silicon halide precursor comprises one or more of the following: SiI_4, $HSiI_3$, H_2SiI_2, H_3SiI, Si_2I_6, HSi_2I_5, $H_2Si_2I_4$, $H_3Si_2I_3$, $H_4Si_2I_2$, H_5Si_2I, Si_3I_8, HSi_2I_5, $H_2Si_2I_4$, $H_3Si_2I_3$, $H_4Si_2I_2$, H_5Si_2I, $MeSiI_3$, Me_2SiI_2, Me_3SiI, $MeSi_2I_5$, $Me_2Si_2I_4$, $Me_3Si_2I_3$, $Me_4Si_2I_2$, Me_5Si_2I, $HMeSiI_2$, HMe_2SiI, $HMeSi_2I_4$, $HMe_2Si_2I_3$, $HMe_3Si_2I_2$, HMe_4Si_2I, H_2MeSiI, $H_2MeSi_2I_3$, $H_2Me_2Si_2I_2$, $H_2Me_3Si_2I$, $H_3MeSi_2I_2$, $H_3Me_2Si_2I$, H_4MeSi_2I, $EtSiI_3$, Et_2SiI_2, Et_3SiI, $EtSi_2I_5$, $Et_2Si_2I_4$, $Et_3Si_2I_3$, $Et_4Si_2I_2$, Et_5Si_2I, $HEtSiI_2$, HEt_2SiI, $HEtSi_2I_4$, $HEt_2Si_2I_3$, $HEt_3Si_2I_2$, HEt_4Si_2I, H_2EtSiI, $H_2EtSi_2I_3$, $H_2Et_2Si_2I_2$, $H_2Et_3Si_2I$, $H_3EtSi_2I_2$, $H_3Et_2Si_2I$, and H_4EtSi_2I.

In some embodiments, a silicon halide precursor comprises one or more of the following: $EtMeSiI_2$, Et_2MeSiI, $EtMe_2SiI$, $EtMeSi_2I_4$, $Et_2MeSi_2I_3$, $EtMe_2Si_2I_3$, $Et_3MeSi_2I_2$, $Et_2Me_2Si_2I_2$, $EtMe_3Si_2I_2$, Et_4MeSi_2I, $Et_3Me_2Si_2I$, $Et_2Me_3Si_2I$, $EtMe_4Si_2I$, $HEtMeSiI$, $HEtMeSi_2I_3$, $HEt_2MeSi_2I_2$, $HEtMe_2Si_2I_2$, HEt_3MeSi_2I, $HEt_2Me_2Si_2I$, $HEtMe_3Si_2I$, $H_2EtMeSi_2I_2$, $H_2Et_2MeSi_2I$, $H_2EtMe_2Si_2I$, $H_3EtMeSi_2I$.

In some embodiments, a silicon halide precursor comprises one or more of the following: $HSiI_3$, H_2SiI_2, H_3SiI, $H_2Si_2I_4$, $H_4Si_2I_2$, H_5Si_2I, MeSiI3, Me_2SiI_2, Me_3SiI, $Me_2Si_2I_4$, $Me_4Si_2I_2$, $HMeSi_2I_2$, $H_2Me_2Si_2I_2$, $EtSiI_3$, Et_2SiI_2, Et_3SiI, $Et_2Si_2I_4$, $Et_4Si_2I_2$, and $HEtSiI_2$. In some embodiments a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen, sixteen, seventeen, eighteen, nineteen or more compounds selected from $HSiI_3$, H_2SiI_2, H_3SiI, $H_2Si_2I_4$, $H_4Si_2I_2$, H_5Si_2I, $MeSiI_3$, Me_2SiI_2, Me_3SiI, $Me_2Si_2I_4$, $Me_4Si_2I_2$, $HMeSi_2I_2$, $H_2Me_2Si_2I_2$, $EtSiI_3$, Et_2SiI_2, Et_3SiI, $Et_2Si_2I_4$, $Et_4Si_2I_2$, and $HEtSiI_2$, including any combinations thereof. In certain embodiments, the silicon halide precursor is H_2SiI_2.

In some embodiments, a silicon halide precursor comprises three iodines and one amine or alkylamine ligands bonded to silicon. In some embodiments silicon halide precursor comprises one or more of the following: $(SiI_3)NH_2$, $(SiI_3)NHMe$, $(SiI_3)NHEt$, $(SiI_3)NH^iPr$, $(SiI_3)NH^tBu$, $(SiI_3)NMe_2$, $(SiI_3)NMeEt$, $(SiI_3)NMe^iPr$, $(SiI_3)NMe^tBu$, $(SiI_3)NEt_2$, $(SiI_3)NEt^iPr$, $(SiI_3)NEt^tBu$, $(SiI_3)N^iPr_2$, $(SiI_3)N^iPr^tBu$, and $(SiI_3)N^tBu_2$. In some embodiments, a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiI_3)NH_2$, $(SiI_3)NHMe$, $(SiI_3)NHEt$, $(SiI_3)NH^iPr$, $(SiI_3)NH^tBu$, $(SiI_3)NMe_2$, $(SiI_3)NMeEt$, $(SiI_3)NMe^iPr$, $(SiI_3)NMe^tBu$, $(SiI_3)NEt_2$, $(SiI_3)NEt^iPr$, $(SiI_3)NEt^tBu$, $(SiI_3)N^iPr_2$, $(SiI_3)N^iPr^tBu$, $(SiI_3)N^tBu_2$, and combinations thereof. In some embodiments, a silicon halide precursor comprises two iodines and two amine or alkylamine ligands bonded to silicon. In some embodiments, silicon halide precursor comprises one or more of the following: $(SiI_2)(NH_2)_2$, $(SiI_2)(NHMe)_2$, $(SiI_2)(NHEt)_2$, $(SiI_2)(NH^iPr)_2$, $(SiI_2)(NH^tBu)_2$, $(SiI_2)(NMe_2)_2$, $(SiI_2)(NMeEt)_2$, $(SiI_2)(NMe^iPr)_2$, (SiI2)$(NMe^tBu)_2$, $(SiI_2)(NEt_2)_2$, $(SiI_2)(NEt^iPr)_2$, $(SiI_2)(NEt^tBu)_2$, $(SiI_2)(N^iPr_2)_2$, $(SiI_2)(N^iPr^tBu)_2$, and $(SiI_2)(N^tBu)_2$. In some embodiments, a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiI_2)(NH_2)_2$, $(SiI_2)(NHMe)_2$, $(SiI_2)(NHEt)_2$, $(SiI_2)(NH^iPr)_2$, $(SiI_2)(NH^tBu)$2, $(SiI_2)(NMe_2)_2$, $(SiI_2)(NMeEt)_2$, $(SiI_2)(NMe^iPr)_2$, (SiI2)$(NMe^tBu)_2$, $(SiI_2)(NEt_2)$2, $(SiI_2)(NEt^iPr)_2$, $(SiI_2)(NEt^tBu)_2$, $(SiI_2)(N^iPr_2)_2$, $(SiI_2)(N^iPr^tBu)_2$, $(SiI_2)(N^tBu)_2$, and combinations thereof.

In some embodiments, a silicon halide precursor comprises two iodines, one hydrogen and one amine or alkylamine ligand bonded to silicon. In some embodiments silicon halide precursor comprises one or more of the following: $(SiI_2H)NH_2$, $(SiI_2H)NHMe$, $(SiI_2H)NHEt$, $(SiI_2H)NH^iPr$, $(SiI_2H)NH^tBu$, $(SiI_2H)NMe_2$, $(SiI_2H)NMeEt$, $(SiI_2H)NMe^iPr$, $(SiI_2H)NMe^tBu$, $(SiI_2H)NEt_2$, $(SiI_2H)NEt^iPr$, $(SiI_2H)NEt^tBu$, $(SiI_2H)N^iPr_2$, $(SiI_2H)N^i$-Pr^tBu, and $(SiI_2H)N^tBu_2$. In some embodiments a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiI_2H)NH_2$, $(SiI_2H)NHMe$, $(SiI_2H)NHEt$, $(SiI_2H)NH^iPr$, $(SiI_2H)NH^tBu$, $(SiI_2H)NMe_2$, $(SiI_2H)NMeEt$, $(SiI_2H)NMe^iPr$, $(SiI_2H)NMe^tBu$, $(SiI_2H)NEt_2$, $(SiI_2H)NEt^iPr$, $(SiI_2H)NEt^tBu$, $(SiI_2H)N^iPr2$, $(SiI_2H)N^iPr^tBu$, $(SiI_2H)N^tBu2$, and combinations thereof.

In some embodiments, a silicon halide precursor comprises one iodine, one hydrogen and two amine or alkylamine ligand bonded to silicon. In some embodiments, silicon halide precursor comprises one or more of the following: $(SiIH)(NH_2)_2$, $(SiIH)(NHMe)_2$, $(SiIH)(NHEt)_2$, $(SiIH)(NH^iPr)_2$, $(SiIH)(NH^tBu)2$, $(SiIH)(NMe_2)_2$, $(SiIH)(NMeEt)_2$, $(SiIH)(NMe^iPr)_2$, $(SiIH)(NMe^tBu)_2$, $(SiIH)(NEt_2)_2$, $(SiIH)(NEt^iPr)_2$, $(SiIH)(NEt^tBu)_2$, $(SiIH)(N^iPr_2)_2$, $(SiIH)(N^iPr^tBu)_2$, and $(SiIH)(N^tBu)_2$. In some embodiments, a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiIH)(NH_2)_2$, $(SiIH)(NHMe)_2$, $(SiIH)(NHEt)_2$, $(SiIH)(NH^i)_2$, $(SiIH)(NH^tBu)_2$, $(SiIH)(NMe_2)_2$, $(SiIH)(NMeEt)_2$, $(SiIH)(NMe^iPr)_2$, $(SiIH)(NMe^tBu)_2$, $(SiIH)(NEt_2)_2$, $(SiIH)(NEt^iPr)_2$, $(SiIH)(NEt^tBu)_2$, $(SiIH)(N^iPr_2)_2$, $(SiIH)(N^iPr^tBu)_2$, and $(SiIH)(N^tBu)_2$, and combinations thereof.

In some embodiments, a silicon halide precursor comprises one iodine, two hydrogens and one amine or alkylamine ligand bonded to silicon. In some embodiments silicon halide precursor comprises one or more of the following: $(SiIH_2)NH_2$, $(SiIH_2)NHMe$, $(SiIH_2)NHEt$, $(SiIH_2)NH^iPPr$, $(SiIH_2)NH^tBu$, $(SiIH_2)NMe_2$, $(SiIH_2)NMeEt$, $(SiIH_2)NMe^iPr$, $(SiIH_2)NMe^tBu$, $(SiIH_2)NEt_2$, $(SiIH_2)NEt^iPr$, $(SiIH_2)NEt^tBu$, $(SiIH_2)N^iPr_2$, $(SiIH_2)N^iPr^tBu$, and $(SiIH_2)N^tBu_2$. In some embodiments a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiIH_2)NH_2$, $(SiIH_2)NHMe$, $(SiIH_2)NHEt$, $(SiIH_2)NH^iPr$, $(SiIH_2)NH^tBu$, $(SiIH_2)NMe_2$, $(SiIH_2)NMeEt$, $(SiIH_2)NMe^iPr$, $(SiIH_2)NMe^tBu$, $(SiIH_2)NEt_2$, $(SiIH_2)NEt^iPr$, $(SiIH_2)NEt^tBu$, $(SiIH_2)N^iPr2$, $(SiIH_2)N^iPr^tBu$, $(SiIH_2)N^tBu_2$, and combinations thereof.

In some embodiments, a silicon halide precursor comprises one iodine and three amine or alkylamine ligands bonded to silicon. In some embodiments, silicon halide precursor comprises one or more of the following: $(SiI)(NH_2)_3$, $(SiI)(NHMe)_3$, $(SiI)(NHEt)_3$, $(SiI)(NH^iPr)_3$, $(SiI)(NH^tBu)_3$, $(SiI)(NMe_2)_3$, $(SiI)(NMeEt)_3$, $(SiI)(NMe^iPr)_3$, $(SiI)(NMe^tBu)_3$, $(SiI)(NEt_2)_3$, $(SiI)(NEt^iPr)_3$, $(SiI)(NEt^tBu)_3$, $(SiI)(N^iPr_2)_3$, $(SiI)(N^iPr^tBu)_3$, and $(SiI)(N^tBu)_3$. In some embodiments a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen, fifteen or more compounds selected from $(SiI)(NH_2)_3$, $(SiI)(NHMe)_3$, $(SiI)(NHEt)_3$, $(SiI)(NH^iPr)_3$, $(SiI)(NH^tBu)_3$, $(SiI)(NMe_2)_3$, $(SiI)(NMeEt)_3$, $(SiI)(NMe^iPr)_3$, $(SiI)(NMe^tBu)_3$, $(SiI)(NEt_2)_3$, $(SiI)(NEt^iPr)_3$, $(SiI)(NEt^tBu)_3$, $(SiI)(N^iPr_2)_3$, $(SiI)(N^iPr^tBu)_3$, $(SiI)(N^tBu)_3$, and combinations thereof.

In certain embodiments, a silicon halide precursor comprises two iodines, hydrogen and one amine or alkylamine ligand or two iodines and two alkylamine ligands bonded to silicon and wherein amine or alkylamine ligands are selected from amine NH_2—, methylamine MeNH—, dimethylamine Me_2N—, ethylmethylamine EtMeN—, ethylamine EtNH—, and diethylamine Et_2N—. In some embodiments silicon halide precursor comprises one or more of the following: $(SiI_2H)NH_2$, $(SiI_2H)NHMe$, $(SiI_2H)NHEt$, $(SiI_2H)NMe_2$, $(SiI_2H)NMeEt$, $(SiI_2H)NEt_2$, $(SiI_2)(NH_2)_2$, $(SiI_2)(NHMe)_2$, $(SiI_2)(NHEt)_2$, $(SiI_2)(NMe_2)_2$, $(SiI_2)(NMeEt)_2$, and $(SiI_2)(NEt_2)_2$. In some embodiments a silicon halide precursor comprises two, three, four, five, six, seven, eight, nine, ten, eleven, twelve or more compounds selected from $(SiI_2H)NH_2$, $(SiI_2H)NHMe$, $(SiI_2H)NHEt$, $(SiI_2H)NMe_2$, $(SiI_2H)NMeEt$, $(SiI_2H)NEt_2$, $(SiI_2)(NH2)_2$, $(SiI_2)(NHMe)_2$, $(SiI_2)(NHEt)_2$, $(SiI_2)(NMe_2)_2$, $(SiI_2)(NMeEt)_2$, $(SiI_2)(NEt_2)_2$, and combinations thereof.

Other Types of Si-Precursors Containing I or Br

A number of suitable silicon halide precursors containing nitrogen, such as iodine or bromine substituted silazanes, or sulphur, may be used in the presently disclosed thermal and plasma ALD processes. In some embodiments silicon halide precursors containing nitrogen, such as iodine or bromine substituted silazanes, may be used in the presently disclosed thermal and plasma ALD processes in which a film with desired quality is to be deposited, for example at least one of the desired WER, WERR, pattern loading effect or/and step coverage features described below.

At least some of the suitable iodine or bromine substituted silicon halide precursors may have the following general formula:

$$H_{2n+2-y-z-w}Si_n(EH)_{n-1}X_yA_zR_w \tag{25}$$

wherein, n=2-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=0 or more (and up to 2n+2−y−z), X is I or Br, E is N or S, preferably N, A is a halogen other than X, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=2-5 and more preferably n=2-3 and most preferably 1-2. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

At least some of the suitable iodine or bromine substituted silazane precursors may have the following general formula:

$$H_{2n-2-y-z-w}Si_n(NH)_{n-1}X_yA_zR_w \tag{26}$$

wherein, n=2-10, y=1 or more (and up to 2n+2−z−w), z=0 or more (and up to 2n+2−y−w), w=0 or more (and up to 2n+2−y−z), X is I or Br, A is a halogen other than X, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon; preferably n=2-5 and more preferably n=2-3 and most preferably 2. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl.

In some embodiments, the silicon halide precursor comprises Si-compound, such as heterocyclic Si compound, which comprises I or Br. Such cyclic precursors may comprise the following substructure:

$$\text{—Si-E-Si—} \tag{27}$$

wherein E is N or S, preferably N.

In some embodiments the silicon halide precursor comprises substructure according to formula (27) and example of this kind of compounds is for example, iodine or bromine substituted cyclosilazanes, such iodine or bromine substituted cyclotrisilazane.

In some embodiments, the silicon halide precursor comprises Si-compound, such as silylamine based compound, which comprises I or Br. Such silylamine based Si-precursors may have the following general formula:

$$(H_{3-y-z-w}X_yA_zR_wSi)_3\text{—}N \tag{28}$$

wherein, y=1 or more (and up to 3−z−w), z=0 or more (and up to 3−y−w), w=0 or more (and up to 3−y−z), X is I or Br, A is a halogen other than X, R is an organic ligand and can be independently selected from the group consisting of alkoxides, alkylsilyls, alkyl, substituted alkyl, alkylamines and unsaturated hydrocarbon. Preferably R is a C_1-C_3 alkyl ligand, such as methyl, ethyl, n-propyl or isopropyl. Each of the three $H_{3-y-z-w}X_yA_zR_wSi$ ligands can be independently selected from each other.

Other Types of SI Containing Precursors

Silicon halide precursors comprising chloride or fluoride may also be used. In such precursor the halogens such as iodide and bromide as described in the above general formula's may be replaced by chloride (Cl) or fluoride (F).

O Precursors

A number of suitable reactants may be used in the presently disclosed processes. These reactant may be used in plasma ALD or plasma CVD processes thereby a layer with a desired quality (at least one of the desired WER, WERR, pattern loading effect or/and step coverage features described below) is deposited.

According to some embodiments, the reactant in a thermal ALD process may be O_2, H_2O, H_2O_2, or any number of other suitable oxygen compounds having a O—H bond.

Silicon Dioxide Film Characteristics

The first silicon dioxide thin films deposited according to some of the embodiments discussed herein (irrespective of whether the silicon halide precursor contained bromine or iodine) may achieve impurity levels or concentrations below about 3%, preferably below about 1%, more preferably below about 0.5%, and most preferably below about 0.1%. In some thin films, the total impurity level excluding hydrogen may be below about 5%, preferably below about 2%, more preferably below about 1%, and most preferably below about 0.2%. And in some thin films, hydrogen levels may be below about 30%, preferably below about 20%, more preferably below about 15%, and most preferably below about 10%.

In some embodiments, the deposited silicon dioxide films do not comprise an appreciable amount of carbon. However, in some embodiments a silicon dioxide film comprising carbon is deposited. For example, in some embodiments an ALD reaction is carried out using a silicon halide precursor comprising carbon and a thin silicon dioxide film comprising carbon is deposited. In some embodiments a silicon dioxide film comprising carbon is deposited using a precursor comprising an alkyl group or other carbon-containing ligand. In some embodiments a silicon halide precursor of one of formulas (9)-(28) and comprising an alkyl group is used in a PEALD or thermal ALD process, as described above, to deposit a silicon dioxide film comprising carbon. Different alkyl groups, such as Me or Et, or other carbon-containing ligands may produce different carbon concentrations in the films because of different reaction mechanisms. Thus, different precursors can be selected to produce different carbon concentration in deposited silicon dioxide films. In some embodiments the thin silicon dioxide film comprising carbon may be used, for example, as a low-k spacer. In some embodiments the thin films do not comprise argon.

According to some embodiments, the silicon dioxide thin films may exhibit step coverage and pattern loading effects of greater than about 50%, preferably greater than about 80%, more preferably greater than about 90%, and most preferably greater than about 95%. In some cases step coverage and pattern loading effects can be greater than about 98% and in some case about 100% (within the accuracy of the measurement tool or method). These values can be achieved in aspect ratios of more than 2, preferably in aspect ratios more than 3, more preferably in aspect ratios more than 6 and most preferably in aspect ratios more than 11.

As used herein, "pattern loading effect" is used in accordance with its ordinary meaning in this field. While pattern loading effects may be seen with respect to impurity content, density, electrical properties and etch rate, unless indicated otherwise the term pattern loading effect when used herein refers to the variation in film thickness in an area of the substrate where structures are present. Thus, the pattern loading effect can be given as the film thickness in the sidewall or bottom of a feature inside a three-dimensional structure relative to the film thickness on the sidewall or bottom of the three-dimensional structure/feature facing the open field. As used herein, a 100% pattern loading effect (or a ratio of 1) would represent about a completely uniform film property throughout the substrate regardless of features i.e. in other words there is no pattern loading effect (variance in a particular film property, such as thickness, in features vs. open field).

In some embodiments, silicon dioxide films are deposited to a thicknesses of from about 1 nm to about 50 nm, preferably from about 3 nm to about 30 nm, more preferably from about 4 nm to about 15 nm. These thicknesses can be achieved in feature sizes (width) below about 100 nm, preferably about 50 nm, more preferably below about 30 nm, most preferably below about 20 nm, and in some cases below about 15 nm. According to some embodiments, a silicon dioxide film is deposited on a three-dimensional structure and the thickness at a sidewall may be around 10 nm.

It has been found that in using the silicon dioxide thin films of the present disclosure, thickness differences between top and side may not be as critical for some applications, due to the improved film quality and etch characteristics. Nevertheless, in some embodiments, the thickness gradient along the sidewall may be very important to subsequent applications or processes.

Example PECVD

A silicon dioxide thin layer was deposited at 550° C. with a plasma power of 600 W at a pressure of about 2.6 torr in a plasma enhanced chemical vapor deposition reactor. The O_2 flow is 4 splm, the Ar flow is 2.8 splm and a seal He flow of 0.28 splm is applied. H2SiI2 is used as the silicon halide precursor. Si precursor was supplied continuously during plasma step.

FIG. **2***a* discloses a wafer map as the CVD layer is deposited. The reflective index RI=1.49. FIG. **2***b* discloses the wafer map of the same CVD layer after 10 min. in 0.5% HF etch. The wet etch rate WERR=2.8 and the DR (Deposition rate)~100 nm/min. The wet etch rate WERR is defined as the wet etch rate of the layer divided by the wet etch rate of the thermal oxide.

FIG. **3***a* discloses a wafer map with a CVD layer which is deposited with the same process as above except that the temperature is lowered to 400° C., which makes the process compatible with the back end of line (BEOL) processes. FIG. **3***b* discloses the wafer map of the same CVD layer after 5 min. in 0.5% HF etch. The WERR=4.1 and the DR~800 nm/min. All experiments were run with an XP8 available from ASM Japan K.K (Tokyo, Japan).

Example PEALD

A silicon dioxide thin layer was deposited at 550° C. with a plasma power of 600 W at a pressure of about 2.6 torr in a plasma enhanced atomic layer vapor deposition reactor. The O2 flow was 4 splm, the Ar flow was 2.8 splm and a seal He flow of 0.28 splm was applied. H_2SiI_2 is used as the silicon halide precursor. The pulse scheme was 0.3 sec/0.8 sec/3 sec/0.1 sec (feed/purge/RF_on/purge). The O is provided continuously during the process. The silicon dioxide layer had the following properties:

TABLE 1

Properties	Data	Remark
Process temperature	400-550 C.	
Uniformity (hi/low stdev %)	2-3.5%	49 pt, 3 mm edge exclusion
R.I @633 nm (1.5K)	1.45-1.48	
D/R (A/min)	0.5-0.7	
WERR	1.1-1.5	0.5% HF
WERR uniformity (hi/low stdev %)	2-4.5%	0.5% HF
Haze (ppm)	0.13	Films seems very smooth
Conformality	75%	Evaluated by pillar test

FIG. **4***a* discloses a wafer map as the ALD layer is deposited. The reflective index RI=1.49. FIG. **4***b* discloses the wafer map of the same ALD layer after 3 min. in 0.5% HF etch. The wet etch rate WERR=1.1, this number is remarkably low because typical high quality PEALD silicon dioxide layers achieve a WERR 2, at best 1.4.

FIG. **5***a* discloses a wafer map with an ALD layer which is deposited with the same process as above except that the temperature is lowered to 400° C., which makes the process compatible with the back end of line (BEOL) processes. FIG. **5***b* discloses the wafer map of the same ALD layer after 2 min. in 0.5% HF etch. The WERR=1.1 revealing the very high quality of SiO2 achieved. Again the experiment have been done with a XP8.

Plasma Treatment

As described herein, plasma treatment steps may be used in formation of a variety of materials to enhance film properties. In particular, utilization of a plasma densification step, for example using an argon plasma, may enhance the properties of dioxide films, such as silicon dioxide films. In some embodiments, a process for forming silicon dioxide films comprises depositing the silicon dioxide and treating the deposited silicon dioxide with a plasma treatment. In some embodiments, the silicon dioxide is deposited by a thermal ALD process, and subsequently subjected to a plasma treatment. For example, silicon dioxide may be deposited by a thermal ALD process comprising a plurality of deposition cycles comprising a first phase in which a substrate is contacted with a silicon halide precursor such that silicon species are adsorbed onto a surface of the substrate, and a second phase in which the silicon species adsorbed onto the substrate surface are contacted with an oxygen precursor. As discussed herein, the silicon oxide deposited by the thermal ALD process may be subject to a plasma treatment, for example after each deposition cycle, at intervals during the deposition process or following completion of the silicon oxide deposition process. Unwanted oxidation due to O plasma exposure is well known issue. However SiO2 plasma processes films have typically much higher quality. It is expected that combining thermal SiO2 deposition and plasma treatment both low oxidation and high quality SiO2 films can be achieved. In some embodiments, silicon oxide is deposited by a PEALD process. In some embodiments, a PEALD deposition process comprises a first phase and a second phase. For example, a first phase of a silicon oxide PEALD process may comprise contacting a target substrate with a silicon precursor such that silicon species are adsorbed onto a surface of the target substrate and a second phase of the silicon oxide PEALD process may comprise contacting the silicon species adsorbed onto the surface of the target substrate with a plasma comprising oxygen in order to form silicon oxide. In this part of the deposition process, the plasma may comprise argon ions. For example, a PEALD silicon dioxide deposition cycle may include contacting the target substrate with a silicon precursor, such as those described herein, and an activated oxygen precursor, for example a plasma of oxygen and argon gas. The target substrate may be exposed to activated argon containing species (e.g., Ar^+ and/or Ar^{2+} ions) in this step, which may, for example, densify the layer. In some embodiments, subsequent to deposition of silicon oxide by PEALD, a second plasma treatment step is carried out. The second plasma treatment step may be carried out after each PEALD cycle, at intervals during silicon oxide deposition, or after the PEALD silicon oxide deposition process is complete. The second plasma treatment step may be an Ar plasma treatment step. The second plasma step may, for example, lead to densification of the deposited silicon oxide film or otherwise improve film properties. Thus, the second Ar plasma treatment step may also be referred to as a densification step. The plasma power and/or duration may be greater in the densification step (second Ar plasma treatment step) than in the first oxygen reactant step, as discussed in more detail below. Therefore a low power may be provided during the O plasma step (to minimize substrate oxidation) and a high power during the Ar plasma step to achieve high quality SiO. The densification step may be carried out after every cycle of a PEALD process, or after various intervals of the PEALD deposition process, as discussed in more detail below.

Thus, in some embodiments, one or more silicon dioxide film deposition cycles can be followed by an argon plasma treatment. Utilizing the argon plasma treatment may facilitate formation of silicon dioxide films having certain desired characteristics. Without being limited by any particular theory or mode of operation, application of an argon plasma treatment may increase a density of the silicon dioxide film formed by the silicon dioxide film deposition cycles. In some embodiments, application of an argon plasma treatment can facilitate formation of a silicon dioxide film which demonstrates increased resistance to wet etch (e.g., as compared to silicon dioxide films formed without an argon plasma treatment, in which the top layer may be easily oxidized and demonstrate similar WERR as that of thermal silicon oxide). In some embodiments, application of an argon plasma treatment can facilitate formation of a silicon dioxide film having increased etch rate uniformity of horizontal surfaces relative to vertical surfaces on 3-D features, decreased wet etch rate (WER), and/or decreased wet etch rate ratio (WERR) relative to thermal oxide (TOX).

In some embodiments, utilizing an argon plasma treatment may facilitate formation of silicon dioxide films useful in applications such as hardmasks, sacrificial layers, gate spacers and/or spacer defined double/quadruple patterning (SDDP/SDQP) in state-of-the-art semiconductor devices such as FinFETs and other multigate transistors.

Although embodiments described herein refer to PEALD deposition of silicon dioxide films, it will be understood that other deposition techniques may also be applicable (e.g., thermal ALD, and/or radical enhanced ALD). Further, the argon plasma treatment may be applied to the deposition of other materials (e.g., metallic materials, dielectric materials, and/or other dioxide materials, such as titanium dioxide (TiO2)).

In some embodiments, plasma power in a PEALD process for depositing silicon dioxide is sufficiently low to reduce or avoid formation of film defects and/or delamination. However, the plasma power may be higher in the argon plasma treatment. Thus, in some embodiments, a plasma power used in an argon plasma treatment is greater than or equal to that used in a PEALD process for depositing silicon dioxide (e.g., an oxygen precursor step of the PEALD process). For example, in a PEALD cycle for forming silicon oxide, a plasma may be formed with a gas comprising oxygen and argon using a reduced plasma power. In some embodiments, a plasma power applied during the argon plasma treatment is up to about 900% that of a plasma power applied during a PEALD process for forming silicon oxide where (e.g., during an oxygen precursor step of the PEALD process). In some embodiments, a plasma power for the oxygen plasma treatment is preferably up to about 400% that of the plasma power used in the oxygen precursor step, more preferably about 100% to about 250% that of the plasma power used in the oxygen precursor step, and most preferably about 100% to about 200% that of the plasma power used in the oxygen precursor step.

In some embodiments, a plasma power used in an argon plasma treatment is less than that used in an oxygen precursor step. For example, a plasma power used in the oxygen plasma treatment can be between about 50% and 100% of a plasma power used in the oxygen precursor step.

Plasma power used in a PEALD silicon dioxide deposition process can depend on various factors, including a geometry of structures and/or material of the target substrate on which the silicon dioxide is deposited. As described herein, plasma power used in a cycle of PEALD silicon dioxide deposition may be about 50 Watts (W) to about 600 W (e.g., in a reaction chamber configured for processing a 300 millimeter (mm) wafer substrate), including for example from about 100 W to about 300 W, and from about 150 W to about 250 W. As described herein, a plasma power applied during an argon plasma treatment may be greater than or equal to a plasma power applied during the precursor step, including for example, about 100 W to about 1000 W, preferably about 125 W to about 600 W, more preferably about 150 W to about 300 W. In some embodiments, a power density of a plasma applied during an oxygen plasma treatment (e.g., in a reaction chamber configured for processing a 300 millimeter (mm) wafer substrate) can be about 0.07 Watts per cubic centimeter (W/cm^3) to about 70 W/cm^3, preferably about 0.08 W/cm^3 to about 0.4 W/cm^3W, and more preferably about 0.1 W/cm^3 about 0.2 W/cm^3. For ignition of the plasma other gases than argon and hydrogen can be added to the plasma.

A duration of the argon plasma treatment can be selected to obtain desired results. In some embodiments the duration is based, in part, on a thickness of the silicon dioxide film being treated. For example, a shorter argon plasma treatment can be used in the argon plasma treatment applied after each PEALD cycle, while a longer argon plasma treatment can be used when the argon plasma treatment is applied less frequently.

As described herein, a silicon dioxide formation process may include a plurality of deposition cycles for depositing the silicon dioxide film and one or more argon plasma treatments steps, where each deposition cycle can include a silicon precursor step followed by an oxygen precursor step. In some embodiments, a cycle including a plurality of deposition cycles (e.g., a deposition cycle including a silicon precursor step followed by oxygen precursor step) and one or more argon plasma treatment steps, can be repeated a number of times. In some embodiments, a plurality of deposition cycles can be repeated to achieve a desired silicon dioxide film thickness, which then can be followed by one or more Ar plasma treatment steps.

In some embodiments, an Argon plasma treatment of a silicon dioxide deposition process can have a total duration of about 1% to about 100% the total duration in which activated hydrogen containing species are provided in the oxygen precursor step, preferably about 5% to about 75% that of the total duration in which activated hydrogen containing species are provided of in the oxygen precursor step, and more preferably about 10% to about 50%.

The frequency with which the target substrate is exposed to the Ar plasma treatment can be selected to achieve desired final film characteristics. For example, one or more Ar plasma treatments can follow a number of repetitions of cycles in which the target substrate is exposed to one or more silicon halide precursors followed by oxygen precursors for silicon dioxide film growth. In some embodiments, cycles of exposing the target substrate to one or more silicon precursors followed by oxygen precursors can be repeated twenty-five times, before each Ar plasma treatment. For example, an Ar plasma treatment can follow every repetition of twenty-five cycles of exposing the target substrate to one or more silicon precursors followed by oxygen precursors. In some embodiments, an Ar plasma treatment can follow every repetition of fifty cycles of exposing the target substrate to one or more silicon precursors followed by oxygen precursors. In some embodiments, an Ar plasma treatment can follow every repetition of one hundred cycles of exposing the target substrate to one or more silicon precursors followed by oxygen precursors.

Without being limited by any particular theory or mode of operation, a plasma Ar treatment can be applied for densification of the silicon dioxide film, such as through ion bombardment of the silicon dioxide film. In some embodiments, a frequency at which an Ar plasma treatment can be applied during a silicon dioxide film formation process can be after about at least every 100^{th} cycle of silicon dioxide film deposition, preferably after at least every 50^{th} and most preferably after at least every 25^{th}.

In some embodiments, a thickness of the silicon dioxide film formed is less than about 3 nm, preferably less than about 2 nm, and more preferably less than about 1 nm, for example such that an etch rate of most or all of the silicon dioxide film thickness can be improved after being treated by an oxygen plasma treatment. In some embodiments, a silicon dioxide film thickness can be less than about 0.5 nm.

In some embodiments, a number of cycles between Ar plasma treatments can be selected based on a trade-off between silicon dioxide film etch properties and throughput. For example, while good etch properties can be achieved with an argon plasma treatment applied after every deposition cycle but will significantly reduce throughput. Thus, the skilled artisan can adjust the treatment ratio in order to form suitable films in the most efficient manner.

In some embodiments, process for depositing a silicon oxide layer includes a multi-step plasma exposure. For example, an hydrogen H plasma can be provided to perform a H plasma treatment. The method may be similar as the argon plasma as described above with the argon replaced with hydrogen. This time it is not high quality/densification that is accomplished. Hydrogen plasma treatment has two effect: the first effect is to provide more reactive sites (—OH surface group) to increase the growth per cycle (GPC) and a second effect of voluntarily creating a high WER to the layer by H incorporation (less dense films). H2 and O2 cannot be mixed in the reactor, so purge steps are necessary between both gases. H2 plasma is typically, but not necessarily generated with Ar, the Ar/H ration should be <10 preferably <4. High power for the H2 treatment will amplify the two effects described above. Higher conformality can also be achieved due to the isotropic nature of H plasma comprising large amount of radical species. Multiple plasma step may be added/combine of Ar and H plasma step in any ratio to achieve desired film properties: high conformality, low or high WERR.

It will be understood by those of skill in the art that numerous and various modifications can be made without departing from the spirit of the present invention. The described features, structures, characteristics and precursors can be combined in any suitable manner. Therefore, it should be clearly understood that the forms of the present invention are illustrative only and are not intended to limit the scope of the present invention. All modifications and changes are intended to fall within the scope of the invention, as defined by the appended claims.

It is to be understood that the configurations and/or approaches described herein are exemplary in nature, and that these specific embodiments or examples are not to be considered in a limiting sense, because numerous variations are possible. The specific routines or methods described herein may represent one or more of any number of processing strategies. Thus, the various acts illustrated may be performed in the sequence illustrated, in other sequences, or omitted in some cases.

What is claimed is:

1. A method of providing a structure by depositing a layer on a substrate in a reactor, the method comprising:

introducing a silicon halide precursor selected from the group consisting of SiI_4, $HSiI_3$, H_2SiI_2, H_3SiI, $Si2I_6$, H_2Si2I_4, $H_3Si_2I_3$, $H_4Si_2I_2$, H_5Si_2I, Si_3I_8, and one or more cyclic compounds in the reactor;

introducing a reactant gas comprising oxygen in the reactor; and,

providing an energy source to create a plasma from the reactant gas so that the oxygen reacts with the silicon halide precursor to form a layer comprising silicon dioxide.

2. The method according to claim **1**, wherein the reactant gas comprises substantially no nitrogen.

3. The method according to claim **1**, wherein the reactant gas comprises less than 5000 ppm nitrogen.

4. The method according to claim **1**, wherein the method comprises a PECVD process.

5. The method according to claim **1**, wherein the reactant gas comprises argon.

6. The method according to claim **1**, wherein a temperature within a reaction chamber of the reactor is between 25° C. and 700° C.

7. The method according to claim **1**, wherein the plasma is remotely generated.

8. The method according to claim **1**, wherein one of the silicon halide precursor and the reactant gas is pulsed to the reactor.

9. The method according to claim **8**, wherein one of the silicon halide precursor and the reactant gas is continuously flowed to the reactor during the method.

10. The method according to claim **1**, wherein one of the silicon halide precursor and the reactant gas is continuously flowed to the reactor during the method.

11. The method according to claim **1**, wherein the silicon halide precursor is continuously flowed to the reactor during the method.

12. The method according to claim **1**, wherein a pressure within the reactor is between about 0.08 Torr and about 40 Torr.

13. The method according to claim **1**, further comprising a plasma treatment step.

14. The method according to claim **13**, wherein the plasma treatment step comprises an argon plasma treatment.

15. The method according to claim **1**, further comprising a hydrogen plasma treatment.

16. A structure formed according to the method of claim **1**.

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